Surf Leg Prosthetic

QL+

Surf Leg Team

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Statement of Disclaimer

Since this project is a result of a class assignment, it has been graded and accepted as fulfillment of the course requirements. Acceptance does not imply technical accuracy or reliability. Any use of the information in this report is done at the risk of the user. These risks may include catastrophic failure of the device or infringement of patent or copyright laws. California Polytechnic State University at San Luis Obispo and its staff cannot be held liable for any use or misuse of the project.

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List of Nomenclature

Al 6061 - Aluminum 6061 is a precipitation hardened aluminum alloy good for marine conditions
Carbon/Epoxy - Carbon Fiber that is made with carbon fibers and epoxy matrix
Ply - One layer of carbon/epoxy
Laminate - Multiple layers of carbon/epoxy that is a final layup
Socket - Connects the residual limb to the adapter and leg
Transtibial - Below knee amputee

Executive Summary

The Surf Leg project was created to meet the challenge presented by Van Curaza of Operation Surf, which teaches veterans how to surf at their events. Operation Surf has military veterans come through the program with transtibial prosthetics made for running or walking that they try to surf with. This style of prosthetic does not allow a user to squat because the ankles are stiff and only flex in one direction. We were challenged to create a new prosthetic ankle. This ankle needed to provide higher mobility for athletes while still being lightweight, adaptable, and water-proof.

Our team consisted of four students and the project was sponsored by QL+ organization. We spent three quarters to research, design, fabricate, and test a prototype that would fulfill the problems requirements. Based on the biomechanics of surfing and customer requirements that Operation Surf has requested, we have designed a transtibial prosthetic leg with four components: ankle, foot, post, and adapter. Our design uses rubber to provide wide ranges of ankle movement, has a carbon fiber foot for flexing and balancing, adjustable post, and universal adapter so that various participants can use the product.

Our team analyzed surfing biomechanics and multiple computer models. We chose a final design using a selection process that analyzes strengths and weaknesses of each design. Using finite element analysis we chose materials that would meet the engineering specifications of the prosthetic leg and weights of the participants. In order to meet the weight range of users we tested four different rubber hardness'.The foot was constructed using carbon fiber and manufactured it in the composite lab. The foot has a high stiffness but allows for torsion and high frequency damping. All the metal parts were made were made using Aluminum 6061. The cap was CNC lathed by Cal Poly and finished by the team on the mill, the posts were lathed by the team, and the baseplate and cross were cut with the water-jet. The carbon fiber was bonded to the metal using a 2 part flex epoxy. The cross was joined to the lower post through welding. All materials were corrosion tested for one month and none of the materials showed significant corrosion effects.

The foot was tested by a volunteer through QL+. She was able to confirm that the ankle provided the necessary mobility, however she gave insight into adjusting the foot size and shape so that it could be walked with more naturally.

Through iterating, fabrication, error, and dedication we produced a transtibial prosthetic that could fit anyone from a teenager to an ex-marine with extreme mobility and flexibility.

Introduction

The Surf Leg Prosthetic project team in conjunction with QL+ and Operation Surf designed a transtibial prosthetic to be used for surfing. The senior project team focused on the missions of QL+ and Operation Surf as they went through the design process during the 2018-2019 academic year. The problem solved was that a standard prosthetic for a transtibial amputee does not provide the flexibility in enough degrees of freedom for a user to squat and balance on a surfboard. The goal of this project was to create a device specifically designed to improve the user's balance and control while surfing. The device was designed with the idea that it could be used by anyone in need of a lower leg prosthetic for surfing at the Operation Surf events, while focusing on a specific user, Kyle Kelly, for testing and dimensions. The lower leg prosthetic fits onto the user's already existing socket. The prosthetic is waterproof and improves upon already existing options for amputees by increasing the user's ankle mobility and angles of the foot for the purposes of surfing.

The project team members are Kurtis Barth (mechanical engineering), Caroline Swanson (mechanical engineering), Samantha Campbell (biomedical engineering) and Oyundari Altansukh (biomedical engineering). The team used their abilities and understandings they have obtained over the course of their college careers at Cal Poly to design and build a prosthetic surf leg. Through the interdisciplinary senior project class they completed the design process, came up with the best solutions for the challenge, and then built and tested the prototype.

Specifications

This prosthetic leg was designed to be adaptable for a variety of potential users because of Operation Surf's large participant turnover. It is important that the prototype aligned with Operation Surf's mission of helping veterans surf with ease and aides them with necessary movements required to surf. The main objective was to design a prosthetic that allows the surfer to stabilize and control the surfboard while carving. Besides this main focus, the prototype also has to be waterproof, comfortable for the user, and stay on while surfing.

First, we had a discussion with Van Curaza and Kyle Kelly about the project and learned the main customer requirements for designing the prosthetic leg. The required movements for surfing includes being able to squat with balance and being able to comfortably pivot on the ankle while in the squatting position. The leg should be able to act as either the front or back leg. It should be durable and waterproof. As for the appearance of the leg, the foot should resemble a biological foot for the self esteem of the user and the post should be adjustable to fits multitude of amputees. The final customer requirement is that the leg has to be able to connect to many different sockets in order to make this leg available for every veteran that participates in Operation Surf.

The engineering requirements outlined in Table 1 are ranked by risk and compliance in order to meet each specification. These specifications were developed through analysis of the customer requirements and target values based on current prosthesis but modified for the purpose of surfing. A Quality Function Deployment (QFD) table in Appendix B was made to analyze and compare the different requirements to ensure the important design aspects of the prosthetic leg and summarized in the table below.

For surfers, one of the most important movements is to be able to squat while keeping their heels on the board for balance and to shift their weight while squatting. A high degree of ankle mobility is required during the ascent and descent of squatting. In upright position, center of pressure is projected at mid-foot and ankle joint is in plantar flexion. When surfing, the prosthetic needs to be able to dorsiflex enough to allow the user to keep the foot firmly planted on the board as it changes angles. During squat, ankle movement shifts from plantar flexion to dorsiflexion ankles and as center of pressure shifts from heel to toe, the ankle joint shifts from dorsiflexion to plantar flexion. The ability to put pressure at the correct angles is what allows the surfer to carve and maintain control while riding a wave.

A walking prosthesis is not designed for these types of complex movements. It is critical for our to have smooth movements over a large range and be adjustable. In order to shift weight while squatting, the ankle joint needs to rotate in multiple directions. It also needs to allow for pronation and eversion of the ankle so the surf board can be controlled and turned. Surfers need more degrees for pronation and eversion for ankle mobility compared to regular squatting. The ankle mobility values in Table 1 have been obtained from research on knee and ankle biomechanics with heels on the ground with shifting weights [15]. Since this will be used in the ocean and in sand, the materials need to be waterproof and resist corrosion to maintain the integrity of the parts. Other general stress and loading considerations must be met in order to prevent failure during use of the prosthesis and to ensure the safety of the user. For the weight of the prosthetic leg, the target value was set to the approximate weight of prosthetic legs available on the market.

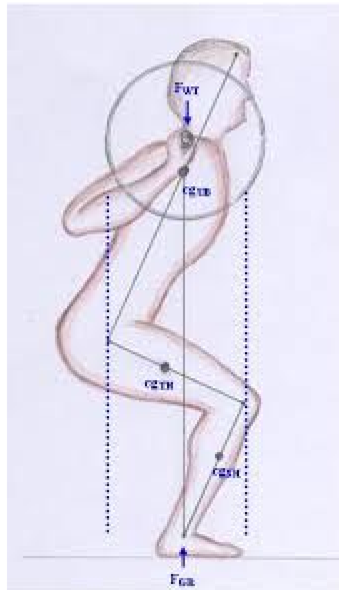


Figure 1: Example of Squatting Position

These engineering requirements will be met and tested in different ways in order to comply with these parameters. Some of the specifications will be met through analysis including hand calculations and FEA to understand the possible failures and design for the correct size and materials. Testing will also be done with mechanical tests as well as user tests to make sure the product performance meets the parameters. Also, it is important to compare the new design to similar existing designs and note how it improves and meets previous available prosthetics. Finally, an inspection will be done to monitor the compliance of these engineering requirements to make sure they are met and the prosthetic functions meet the customer requirements stated above.

Table 1. Project Surf Leg Formal Engineering Requirements

Spec #	Parameter Description	Requirement of Target	Tolerance	Risk	Compliance
1	Corrosion resistant	No visible change	-	H	T,I
2	Bending deflection	0.1 in	+/- 0.1in	L	A, T
3	Buckling	300 lbf	+/- 5 lbf	M	A, T
4	Weight	4 lbs	+/- 1 lbs	L	S, I
5	Friction on Board	0.5	+/- 0.2	M	T,I
6	Dorsiflexion	30 degrees	+/-10 degrees	H	A,T,S,I
7	Plantar Flexion	30 degrees	+/- 5 degrees	M	A,T,S,I
8	Pronation	15 degrees	+/-2 degrees	H	A,T,S,I
9	Eversion	10 degrees	+/- 2 degrees	H	A,T,S,I
11	Degrees of Rotation	3 axis	+/- 1	M	A,T,I
12	Torsion stiffness	40 psi	+/- 10 psi	M	A,T,S

Background

The idea of this project is to build a transtibial prosthetic leg to use while surfing. Current everyday prosthetic legs utilized by amputees have one degree of freedom for ankle movement. Advanced models of the ankle joint are being utilized by current participants in Operation Surf and these models provide dorsal and plantar flexion only. This is done through the use of a shock as seen in the BioDapt Versa foot. This foot performs well for many sports such as cycling, snowboarding and horseback riding. However, the single degree of ankle motion and the flat foot design do not provide mobility required for surfing. When a surfer stands up and carves into a wave they need to be able to perform eversion and inversion of their ankle and pivot while being in a squat position. Without the ability to balance, the amputees are severely limited in their stability while they are standing on the surfboard.

This project will directly benefit the nonprofit organization Operation surf. Operation Surf, a program based in the central coast, uses the ocean to rehabilitate wounded veterans and active-duty military through surfing. The Operation Surf organization was started by Van Curaza in 2009 and since its beginning has had an estimate of over 300 veterans complete its seven day program [4]. The benefits that surfing has had for the veterans can be seen in a study that was conducted by the Air Force Veteran and therapist Russell Crawford. His study concluded that after completion of Operation Surf program, veterans showed a significant increase in self efficacy and a significant decrease in both depression levels and PTSD symptoms [5]. Production of the surf leg will not only allow more transtibial amputee veterans to participate in Operation Surf, but also improve the ability of current transtibial amputees to continue utilizing ocean therapy.

The project started by looking at various ways athletes attach modules to the socket on a residual limb below the knee. Working down to the foot, the goal is to come up with a design that can integrate with multiple adapters in order to equip as many people as possible. From the adapter to the board, the ideal design would provide movement about all three axes. This is done through many different types of adapters that will integrate our design to the socket. Since there are many different types of adapters out there, one of the goals of this project is to create or use a universal adapter so that anyone who goes to Operation Surf will be able to use the Surf Leg. Companies like Endolight have 17 different adapters on their website, each with different designs and ways of connecting the socket to the post [6]. Through our research, we have determined that the two most popular ways the prosthetics attach to the leg is either through a female-male pyramid attachment module or a 4 screw attachment.

Currently there aren’t any prosthetic designs on the market that provide the degrees of freedom needed to surf. However, there is a patent for a water leg in the US patent system. US Pub # 20120095572A1 - Adaptable Water Sports Leg is designed for use in the ocean but maintains only one DOF (degrees of freedom). In the Chinese patent system, there is technology to waterproof biometric sensors and electric powered devices. CN102871781B - Waterproof and dustproof device for powered below-knee prosthesis and production.

It is hard to find a prosthetic design that provides every degree of motion necessary for surfing. Most prosthetics on the market have an ankle design that only allow for plantarflexion and dorsiflexion, without design components for inversion and eversion. The Passive Prosthetic Ankle-Foot Mechanism for Automatic Adaptation to Sloped Surfaces uses a cam mechanism to move the ankle and uses rubber bumpers to neutralize the motion in dorsiflexion and plantarflexion. Using a rubber with durometer of Shore A for a rear bumper to resist the plantar flexion velocity with a stiffness of 0.31 Nm/degrees, and a 60 Shore A polyurethane rubber to resist the dorsiflexion, these materials will help the mechanical design to return to neutral position [7]. This use of rubber bumpers is incorporated into the Surf Leg prosthetic design to limit the ankle movement, so that the ankle does not move too far in any direction, as well as help the athlete return the leg to neutral position without using muscles.

Popular prosthetics, including the leg used by Kyle Kelly at Operation Surf, is made out of a carbon fiber composite. Most walking prosthetics need movement in the ankle as well as energy return to aid in the propulsion phase of walking [8]. For the Surf Leg, this is less important as the user will only be surfing and walking is not considered in this design. However, carbon fiber composite will give some amount of flexibility and stability of the leg as well as a very high specific strength [9]. The use of a split toe was also found on Kyle Kelly’s foot as well as many other feet and a good way to increase the amount of inversion and eversion while balancing on the surfboard.

For the certification of our product the ANSI provides guidelines on how to test the products strength and safety:
ANSI ISO 22523:2006 - Covers strength, materials, restrictions on use, risk and the provision of information associated with the normal conditions of use of both

components and assemblies of components for external limb prostheses and external orthoses.
ANSI ISO 22675:2016 - Cyclic Test, Static Proof Test, and Static Ultimate Test suitable for the certification of ankle-foot devices

Design Development

Design Concept Generation

When we began this project, we gathered background information on ankle biomechanics for surfing and other similar activities. That allowed us to gauge the motion our prosthetic foot must perform, and also understand the pressure that is applied at those ankle angles. We continued our research by searching and analyzing the current market for waterproof and surfing prosthetic ankles. We then talked with our challenger, as well as interviewed individuals that currently use prosthetics to surf, we identified the needs of the prosthetic. The needs of the challenger and interviewed individuals were then changed to engineering metrics for testing and customer satisfaction.

The requirements and use for this prosthetic helped us as we began the iteration process for designing the prosthetic. We created many concepts for the prosthetic, and each were analyzed for their strengths and weakness as we continued to modify and add detail to the prosthetic leg. We then submitted out conceptual designs to the challenger to gain their input and approval. Their input was used to modify the concepts and change the design, until a final design was agreed upon. Once the final design was agreed upon, materials were researched to help the design perform optimally.

From the materials selected, we created a prototype to be tested to ensure the design performs as expected and meets our project engineering requirements. We started out by 3D printing our design for functional movement. Stress tests and fatigue tests were planned to be performed on the prosthetic to ensure that the prosthetic can be used in a high impact environment such as the ocean, and that the prosthetic would not break during a wave ride. Unfortunately we were unable to develop apparatus for testing the foot. This requirement was met through the functional live testing with an amputee volunteer. Material tests will be done in the form of a corrosion test that will examine the prosthetics ability to be used in the ocean environment.

These tests provided insight into how the final design of the prosthetic should be modified and changed. Once we are satisfied that the engineering metric are met for an optimal outcome we will then perform a final test, done by a human volunteer using the prosthetic. The volunteer provided insight into the mobility of the foot. However when it came to present the product for challenger testing their was not an amputee who could surf available until after the completion of the project.

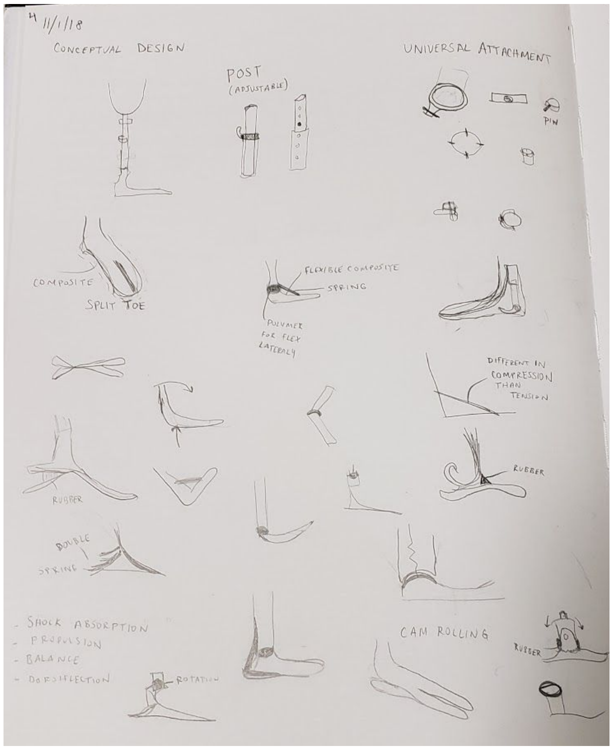
To come up with concepts we used the techniques of functional decomposition to define the functions that are necessary for our design to have, without overly defining the results we wanted. Then we brainstormed the means of achieving that, with ways to meet that criteria. We also came up with ideas by using empathy to consider their needs and how they would feel about the design. This was important in considering the shape and look of the prosthetic to make it look more like a biological foot. From there, we also created categories for components and wrote sticky notes on how to achieve those requirements with as many different ideas as possible. Through this process we were able to come up with more ways of attaching things without worrying about the feasibility of manufacturing or other aspects, but focused on just the possibilities of it completing that singular function.

Another way to generate ideas was through background research and patent searching. We used the research results to come up with design concepts, use some aspects of other designs to spark ideas for our project or modify those ideas for the purpose of our project. From there we made 30 conceptual prototypes out of basic materials, such as foam board, hot glue, corks, rubber bands, and wood skewers. This allowed us to be creative with our design and quickly ideate many different physical prototypes. We used these prototypes and refined them a few times while getting feedback from Van, to come up with our concept.

For our conceptual design review we presented a concept to the class and Van. After presenting the concept to Van, we have decided to modify our design to incorporate his vision of the leg. Thus, we have finalized our design and the details of final design is described below.

Design Idea Selection

In the process of selecting our design we tried to explore many potential solutions that implemented a wide variety of materials, movement, and design. When selecting the design ideas we focused on a few key concepts. These were strength, durability, corrosion resistance, adaptability, and range of motion. For us the most critical characteristic in the design is range of ankle motion. The ankle component needs to flex like a biological ankle in a full squat. Originally, we neglected ankles that did not have the potential to provide rotation the tibia/fibula bone. However, after evaluating motion, we decided that this movement could be gained from the flex in the other degrees of freedom.



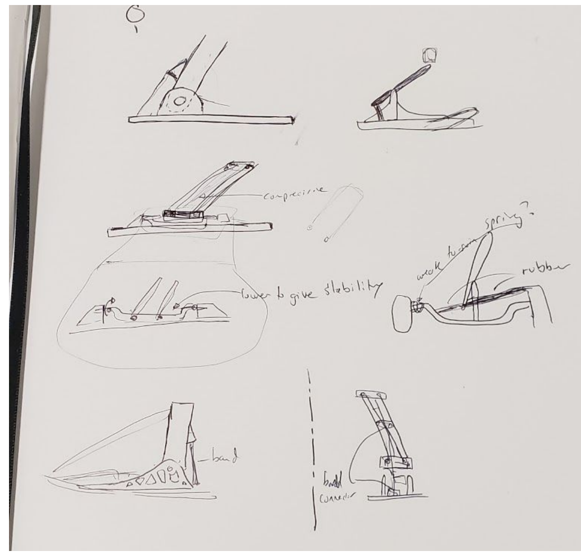


Figure 2: Various foot parts designs

Figure 3: Multiple Designs for the ankle

Our preliminary designs focused on providing a flex motion with respect to the board. In preliminary models, this function was attained by using a ball shaped foot that would roll on the board to rotate. Another design featured a cross shaped foot with springs connected in each direction to provide resistance. After meeting with our sponsor, we learned that neither of these ideas would satisfy their requirements. The first foot would not work because surfboards get wet and waves are bouncy. This foot most likely won’t provide the necessary traction. The second foot referenced would not work for two reasons. The first is that the foot needs to look as similar to a biological foot as possible in order to support the esteem of the athlete. The second reason is because the large cross shape would create a lot of drag in the water. This drag is very detrimental to someone paddling into a wave and might prevent them from reaching a critical velocity while standing up. Our third design selection was a recurve carbon foot with one solid attachment where we would implement the ankle motion. To help with traction and full lean, the sponsor recommended fastening a soft shoe outsole larger than the carbon footprint to the bottom of the foot.

When designing the ankle, we started out by using a ball and socket joint for inspiration. Of all standard joint types this was the closest movement to our foot. Van, our sponsor, liked the idea of using a design akin to a shaft in a lacrosse ball as a motion guide. While this design provided the desired motion and return to normal for plantar/dorsiflexion and ankle roll, there was too much freedom of rotation about the tibula/fibula axis. The next designs looked into using U-joints for as the primary movement design. However the space required for the U-joint and kinetic material was much to large for the needed strength. For our conceptual design our inspiration for the ankle came from skateboards. By using a skateboard truck for ankle lean and then placing the second axis of rotation where the wheels are the system had all the movement needed in a compact space. From there we expanded on the joint of the skateboard truck and the idea of the bushing that allows movement but also is a stable joint. Using that and the idea of the lacrosse ball rubber we came up with our final design.

For our design to be adaptable we needed it to fit as many people as possible. Because not all users will have the same leg length the foot needs some adaptability in height. Not all users will have the same attachment model on their socket so we need a universal connector design too. When adapting to multiple size legs we looked at two main options. The first style was similar to twist backpacking poles. A drawback to this concept is that because our leg will transmist torsion the post could turn and allow the bottom half of our foot to fall completely off. The other method of adjustment was similar to crutches. Crutches are designed to handle very high loads and have been tested for years, which saves us from having to validate their strength. We also considered a bicycle seat post clamp, that will provide a clamping force high enough to hold the post, but also allow adjustment.

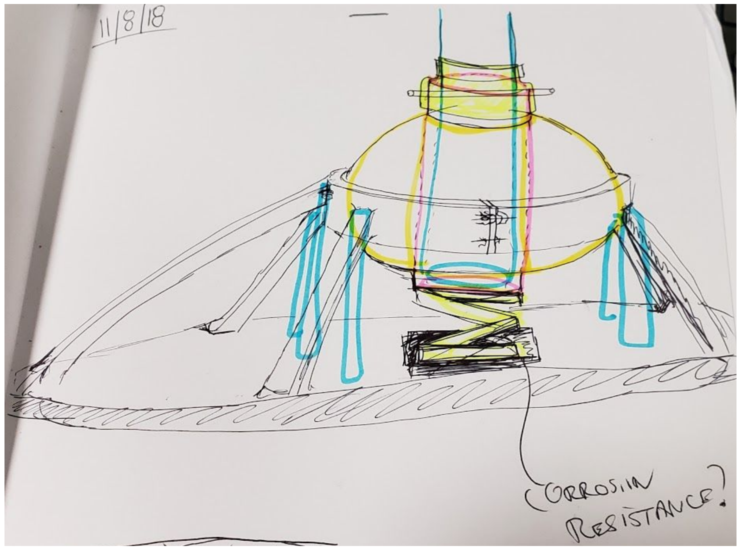


Figure 4: Design idea that attempts function like a u-joint without moving parts

The other part of adaptability is the universal adaptor. The universal adaptor was researched considering the different ways that prosthetic legs are connected to the socket. Many ideas for this concept ranged from a magnetic sleeve to be placed over the socket, to a metal appliance that could be connected to many different sockets. Both designs provided problems in verification that they would be able to perform under the maximum load without slipping. We also did research on current adaptors that are currently on the market, this would cut down on the manufacturing. The current adaptors on market are four hole to pyramids adaptor, or pyramid to four hole adaptors.

Description of the Final Design

Description of Overall Final Design

The final overall design can be seen in Figure 5 below and incorporates four major components including the foot, ankle, post, and adapter. The foot is made out of carbon/epoxy and configured up in a way to provide flexibility as well as stability. The foot allows extension, bending, and twisting of the composite. The ankle is made with a baseplate bonded to the foot that acts like a washer to distribute force from the assembly. There are two rubber parts, acting like bushings to allow constrained motion as well as assist in returning the ankle to the neutral position. The bottom rubber allows the post to dig in and the cross at the bottom of the post stops the post from completely spinning when a torque is applied. The top rubber is the main resistance for the ankle and provides the movement necessary for surfing. The rubber allows motion as well as gives the proper resistance to maintain control and return the leg to the proper position. The shell on top of the rubberl holds down the assembly and bolts into the baseplate as well as act as a hard stop for the post. The lower post has a cross on the bottom and the upper post goes over the bottom post and is secured with a bicycle tube clamp. The upper post has three possible sizes to allow adjustability for multiple users. A universal female adapter is attach on top of the upper post to the bottom of the socket. This allows most sockets to easily attach to the prosthetic and allows for the most number of users to enjoy the use of the leg.

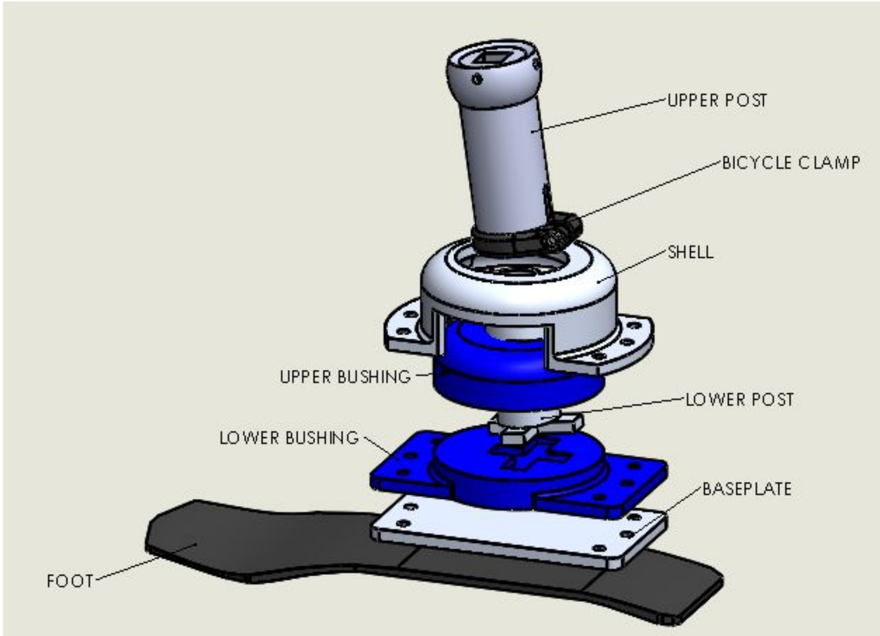


Figure 5: Layout drawing of complete assembly

Ankle Final Design

The final design of the ankle incorporates the initial skateboard bearing idea of using a pad to provide the compression, however we adapted the design to allow torsion and flexing in two directions. The final design of the ankle is composed of a baseplate, two rubber pads, a cap or shell, and the post. The rubber bushings holds the base of a post which has a special cross that prevents the ankle from twisting within the two rubber bushings. Not only does this cross control twisting but it also prevents the post from coming out or rotating too far forward. The neutral position of the post is eight degrees forward. The bottom of the post is positioned slightly aft in the shell so that the top comes out in the center. The purpose of the aggressive neutral stance is to mimic that “attack” stance required by surfing and most other sports in which the foot would be used. The upper and lower bushing are compressed into place by the shell and baseplate.

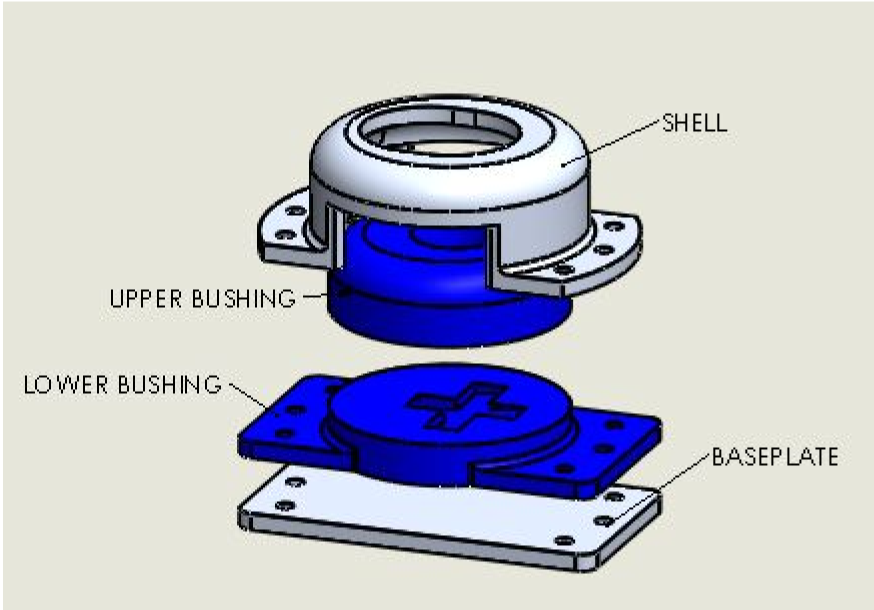


Figure 6: Ankle components exploded view

The shell and baseplate are both manufactured from Aluminum 6061 to have a high corrosion resistance and high strength. This metal was chosen because it was a good combination of properties. The two most important were strength and corrosion resistance, but the metal also needed to be easy to manufacture and reasonably priced. The baseplate was cut using the water-jet from 1/4” sheet metal and the shell is made from 6” Aluminum round bar. Each part has a bolt pattern for six 1/4” countersunk bolts and nuts. The nuts allow a hand adjustment on the tightness of the bushings and easy swapping between stiffer and softer rubbers.

The rubbers that we used run between 600 psi to 2000 psi. During normal use the ideal motion would be for the post to flex 1/2 to 2/3 of the possible range. The post should not hit the shell under normal use, as this will be jarring and may unbalance the athlete, but will act as a hard stop if necessary.

Foot Final Design

For the design of the foot we choose to make a composite laminate approximately the size and shape of a human foot. The foot is made out of carbon/epoxy prepreg Uni-tape of TenCate material, with specifications in Appendix E below. This material was chosen because carbon/epoxy laminates have high specific strengths as well meets our material corrosion specifications. Carbon/epoxy does have some hygrothermal effects such as warping and residual stresses, however with our environment of the ocean and outdoors these effects are negligible and therefore not analyzed. For the analysis of the composite see Appendix E with MATLAB code for three different laminate configurations.

The shape of the foot is approximately 12 inches by 3 inches and shaped in a way to give the athlete confidence as our specifications required. This shape shown in Appendix B was cut out of the prepreg material and all the edges were broken to avoid the foot digging into the top of the foam surfboard, as well as not injury the athlete if the foot hits their other leg. The foot has a slight bend in the arch area to allow more flexibility and plantar flexion compliance as well as have a spring effect to aid in returning the leg to the neutral position.

A surfing bootie was put around the foot to again help avoid the foot digging into the board, create friction between the board and foot, and keep more sand out of the components. To attach the composite foot to the bottom ankle plate we used a flexible epoxy, see specification sheet in Appendix D, to adhere the top of the composite to the bottom Aluminum baseplate. Since Aluminum and carbon fiber is known to create a galvanic cell layer a thick coat of epoxy was put on both on top of the carbon/epoxy and on the baseplate before compressing them together.

For composite analysis basic lamina and laminate theories were used to determine the stiffness matrices and the optimum laminate layup configuration. This foot needs to be able to flex in the arch area as a natural foot would and spring back to the original position. That means there needs to be extensional stiffness in the fiber direction from heel to toe. There also needs to be the ability to bend and flex in that area without fracturing. The original design and the pugh matrix from Appendix A indicates that a split toe design would be advantageous to allow more inversion, eversion, and flexibility in the toes. However, our final design will not have this split toe design because the laminate can be designed instead with the correct configuration to allow that motion without cutting the fibers. The effects of cutting the laminate down the middle would mean the strength of the fibers would severely decrease because they would be cut and would make the laminate lose some performance aspects of the design. So the final design will allow for bending of the arch, extension of the laminate in tension, shear coupling and twisting in the toes, and overall stability of the foot.

The layup configuration of all the laminates considered are symmetric balanced. This is because that will provide the necessary structural mechanics for this application. A symmetric laminate means that across the line of symmetry the fiber angles are in the same location symmetrically with respect to the midplane. A balanced laminate means it has a ply of the same angle but opposite sign across the midplane from that ply. Composites behave as orthotropic materials which is a special case of anisotropic materials with three mutually perpendicular planes of symmetry. This means there is no coupling between shear and normal stress and strains, or between planes. The material properties can be related with engineering constants of young's moduli, poisson's ratios, and shear moduli for each direction. For this study only in-plane lamina theory was applied to the laminate. The mechanical relationship between stress and strain is found using a stiffness matrix. Inverting the compliance matrix and reducing it using assumptions of in-plane and 2D loading we get the reduced stiffness matrix Q. With that matrix since each fiber is oriented at a different angle, the Q matrix has to be transformed into that direction to match the global and lamina directions. Each ply has its own rotated Q matrix that becomes $\overline{Q}$. Then the laminate compliance and stiffness matrices are calculated using the reduced stiffness matrices for each lamina. The A matrix is the extensional stiffness matrix and determines the ability of the matrix to extend in tension or compression. The B matrix is the coupling matrix, this determines how the composite will perform with coupling of shear and normal forces and twisting. The D matrix is the bending matrix and allows the composite to bend in certain ways to the desired amount. These are all calculated as seen in Appendix E composite foot analysis.

With the composite analysis done for the stiffness matrices and basic knowledge of composites the different values are considered and compared. Having 0 degree plies allows for extension in tension along the longitudinal heel to toe direction and effects the A matrix the most by making the terms non-zero which means it will flex in that direction. The 90 degree plies help with bending and makes the D matrix non-zero, allowing the compliance necessary. The ± 45 degree angle plies will make the foot twist and therefore make the B coupling matrix non-zero. These are the desired performance results for the foot. To decide the layup with these angles in mind the number of plies is varied and the matrices are compared.

For Laminate 1 the layup configuration is $[0_3/90/0_3/\pm45_2/0_2]_{s.}$ This means that there are three 0 plies, one 90, one +45, one -45, one +45, one -45, and two 0's. That is all symmetric so the same thing is reflected across the midplane creating a total of 26 plies. Laminate 2 has the same basic configuration with less 0 plies to make the laminate thinner and less stiff. The configuration is $[0/90/0/\pm45_2/0]_s$ with a total of 16 piles. Laminate 3 is made specifically for the toes only with a configuration of

$[0_2/\pm45_2/0_2]_s$ with only 14 plies. It differs from the other laminates in that it doesn't have a 90 degree plies, because it doesn't need the same bending compliance as the arch of the foot. It only has 0's and 45's to allow for twisting in the toes along the 45 degree angle to allow inversion and eversion in the toes. The other configuration have this, but with 90's and more 0's which makes the laminate overall stiffer.

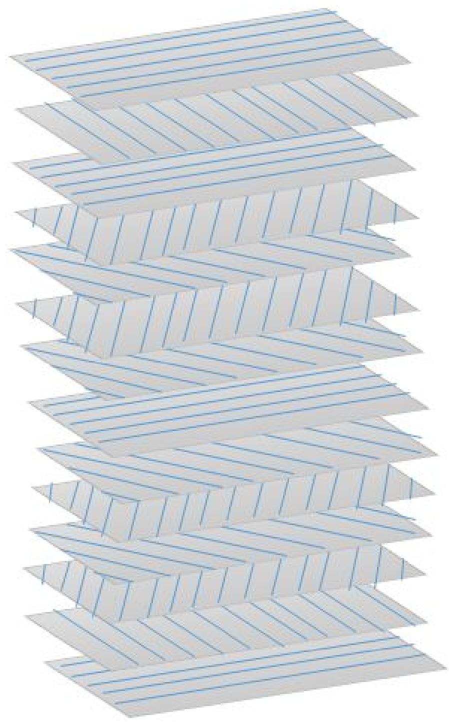


Figure 7: Layup Configuration Example for Layup 1

Comparing the A, B, D matrices for Laminate 1 and Laminate 2, as seen in Attachment E, Laminate 1 is stiffer than Laminate 2 as expected. That is because it has more plies overall with 26 compared to 16 respectively. All the matrices have non-zero values which indicate they will perform as expected and comply with the correct movements necessary. The terms in the 1,1 and 2,2 positions in the matrix means that it will perform will in the 1 direction, which is heel to toe longitudinal direction, and 2 is perpendicular across the lateral to medial side of the foot. The 1,6 and 2,6 positions in the matrix are actually the 1,3 and 2,3 but since it is the reduced stiffness matrix it is the shear components so those are more flexible for Laminate 2 than Laminate 1 meaning it will allow more twisting. The D matrix shows that there will be bending in the 1,1 and 2,2 direction with smaller effects in the shear, which is good. We want the composite to bend in the 2 direction and create the arch effect. Laminate 3 shows that there are zero terms for the A and B matrices 1,6 and 2,6 terms. That means that there is not good in-plane shear compliance because the 90 degree plies were taken out it will not bend well. That is fine for the toe design because the toes only need to twist and extend as they will as the rest of the A, B, D matrices indicate.

For the final design we will make these first two laminate layups and decide what stiffness is appropriate for our design. With basic lamination theory applied it is not possible to further analyze these composites, so testing will be done to finalize the number of layers. The final design will use either Laminate 1 or 2 and taper off slowly into the toes with the toe configuration of Laminate 3. Since the metal plate is used as a washer to distribute the force this plate will dominate the stiffness in that area, so the composite does not have a big effect there. It is important to move the arch so that the foot will bend, but at the end of the bend the layers of 90 degree plies and 0's will taper off to only have the plies indicated in Laminate 3. This will allow the foot to have the performance aspects desired in each location and overall be the best designed composite.

Upper Post Final Design

To create the adjustability requested by our challenger, the post is similar to a two part bicycle seat post. The post consists of a bottom post, which was discussed in the ankle final design, and an upper post. This two-post design utilizes different length upper posts to create the adjustability range for the differing lengths of residual limbs. The upper post fits over the bottom post and secured with the bike clamp to provide more height ranges.

The upper post will need to maintain at least a 0.5" overlap with the bottom post at all times during use. Utilizing the overlap, the longest post was calculated to be 9.5". Due to the ability to overlap the corresponding next two lengths were calculated by the minimum lengths of each, until the upper post created a length that was about equal to the bottom post length. After the calculations, three upper post lengths were identified. These three lengths are 9.5", 6.5" and a 3.5" upper post. For the calculations of upper post length, please refer to Appendix E: Upper Post Length Analysis.

The 0.5" overlap is also due to the 0.5" slit that is located at the bottom of the posts..The overlap protects and minimizes foreign particles from entering form the environment. This slit is essential to the post, because it will allow for the bike clamp to have a stronger clamping force on the pipe. Four slits are cut into the post for maximum clamping power to ensure that the pipe will not slip when force is applied to it.

Figure 8: Model of the 3.5” upper post

To ensure that the upper post is able to connect to the socket, a female pyramid post clamp adaptor is used from Figure 9. This adaptor allows for the different post lengths to connect to the adaptor on the bottom of the socket.

Figure 9: An example of a female pyramid tube clamp adaptor

Adapter Final Design

For our adaptor, we have chosen to proceed with purchasing a four hole to male pyramid adaptor (Figure 10). We made this decision after analyzing the different forms in which a prosthetic is attached to a socket, and found that the majority use either the four hole connection or a pyramid connection. After analyzing the different adaptors available on the market, we found that the four hole to male pyramid adaptor was our best option. The adaptor we chose is lightweight and add the least amount of height to the prosthetic. The adaptor is made from titanium, which has excellent corrosion resistance to saltwater.

Figure 10: An example of a four hole male pyramid adaptor

Material Selection

Our final design consists of four major components and materials for each component were selected so that the design meets the engineering specifications previously stated in Table 1. First, using the rubber shore hardness durometer scale, we have determined that the rubber hardness that will provide the ankle movements required for surfing would be in between shore A 70-85. Shore A70 is used for tire threads and A85 is used for shoe heels [21]. We also made more rubber parts with durometers of Shore A44 used for pencil eraser and Shore A30 which would be softest rubber part [2]. Using this approximation, the exact rubber hardness to be used for final design would be determined through rubber hardness testing and based on the specific user. For this test, we will cast multiple rubber components with different hardness and analyze the range of motion of the post when weight is applied at an angle. From the test, the rubber hardness that allows the post to move in the range of ankle movement required in Table 1 will be chosen for further manufacturing process. The details of the test is included in the Verification and Testing section and in Table 5.

The metal parts of the ankle will be Aluminum 6061. The metal was chosen through researching metals used for marine application with high resistance to corrosion. The Al 6061 is reported to have an excellent joining characteristics, good acceptance of applied coatings, has relatively high strength, good workability, and high resistance to corrosion [20]. One of the advantages of using Al 6061 is that it is widely available in different shapes and sizes. Some of the applications listed for Al 6061 include aircraft and marine fittings, hydraulic pistons and bike frames [20]. The important mechanical properties for Al 6061 are ultimate bearing strength of 88 ksi, bearing yield strength of 56 ksi and fatigue strength of 14 ksi [19]. Taking these properties into consideration, the high resistance to corrosion, and workability, we chose Al 6061 for the metal parts. The size and shape of each metal part to be purchased was determined by the geometry of the conceptual model of the final design. The detailed drawing of the parts are included in Appendix C.

For the adapters, there is a wide range of adapters available on the market with different materials and product specifications. The most common materials include stainless steel, aluminum and titanium. The titanium adapters have the highest load criteria of 300 lbs compared to stainless steel load criteria of 265 lbs and aluminum load criteria of 220 lbs [17]. Since the prosthetic is designed to be used by multiple users, we chose the highest criteria of load and decided to purchase the titanium adapters for our final design.

For the composite material we will be using carbon/epoxy because of its specific strength and corrosion resistance. We will be using the material available to us from the Cal Poly Mechanical Engineering Composites Lab. The material is specified below in Appendix D.

Cost Breakdown

The cost breakdown for the project is divided into two sections: the testing materials and manufacturing materials. Table 2 shows the cost for testing materials and prototype materials without shipping and tax. Cost includes the 3D printing material rubber hardness testing materials, and the price of the salt for corrosion testing.

Table 2: Cost for Testing

Test	Material	Cost
3D Printing	Ultimaker NFC PLA-Blue	$49.95
Rubber Tests	MAX Mold 20 (2)	$27.25 x2
	Ease Release Spray	$13.86
Corrosion Testing	Sodium Chloride	$87
Total		$205.31+tax+shipping

The material cost for manufacturing a single prototype is shown in Table 4. These values have been taken from our purchasing history and reflects the materials we purchased that made it into the final product. Some of the materials have been graciously donated to our group, these items and the prices of these items have been placed in table 4 and these items have been indicated. Table 4 also includes the price of outsourcing the manufacturing of the metal cap. For the other items were manufactured in house by the Surf Leg, therefore there are no manufacturing costs for parts other than the metal cap. The total cost of the materials we purchased came out to $925.51, disregarding shipping and handling. This production cost is for a one time manufacturing of the product. For mass manufacturing the price would be lower considering that many of these materials are in quantities that would allow for use to manufacture multiple prosthetic surf legs. The total cost of the project is $1,130.82; this cost was calculated by adding material costs, manufacturing cost and testing cost

Table 3: Cost for Materials and Manufacturing

#	Part	Material	Cost
1	Metal Plates	Al Sheet 12”x12”x .25”	$27.48
2	Metal Cover + production cost	Al Rectangular Bar 2”x4”x12”	$280.71 + $120
3	Standard-Wall Aluminum Pipe	Al Round Tube 1-5/16”x .25”x36”	$42.86
4	Thick-Wall Aluminum Unthreaded Pipe	Al Round Tube 1-¼” x 0.91” x 36”	$55.91
5	Bike Clamp	Al 7076	$9.36
6	Liquid Rubber	PT Flex 70 Liquid Rubber 4lb	$66.00
7	Female Pylon Adapter	Titanium Tube Clamp Adapter	$33.25
8	Pylon to Socket Adapter	Titanium 4 Hole Male Pyramid	$46.44
9	Epoxy	G/Flex Epoxy	$20.00
10	Connectors	6 x 1/4” Countersunk Bolt	$1.00
11	Connectors	6 x 1/4” Fly Wing Nut	$1.00
12	Rubber	PT Flex 85 Liquid Rubber	$66.00
13	Rubber*	PT Flex 35 Liquid Rubber	$66.00
14	Rubber*	PT FLex 44 Liquid Rubber	$66.00
15	Carbon Fiber*	Carbon Fiber composite	$40.00
16	Water shoe	Rubber and neoprene	$23.50
		Total	$925.51

*indicates the item had been donated to the Surf Leg Team

Safety Considerations

The surfing prosthetic leg is designed to be used for surfing and is designed to support surfing movements by allowing ankle movement for squatting. The design is not suggested for walking for a longer period of time than the amount required for surfing as walking in the prosthetic for a long time might affect hip joints and knee joints. The design is generally not recommended for everyday use as it is not customized for individuals and lacks the customization required. Since the product will be used in the turbulent condition of the ocean, necessary precautions should be taken before surfing with the surf leg. These precautions would be to check the screws, the adapter connections and clamps to ensure it is ready to be used and locked down. The safety checklist for this project is included in Appendix G for detailed list of safety considerations.

Maintenance and Repair Consideration

One of the maintenance required for the prosthetic leg would be to change the rubber components when necessary. Once the rubber wear affects the performance of the component and no longer provides the ankle movement and resistance, it should be switched with a new rubber. This is done by disassembling the prosthetic, removing the old rubber, placing new ones and reassemble. More rubber bushings can be cast from 2 part rubber kits with the custom silicone molds.

Another maintenance consideration would be to wash the components with tap water and dry them out after each use. This would remove all the salt, sand and any metal oxide on the surface protecting from crevice and metal corrosion to increase the lifetime of the parts.

Product Realization

Manufacturing Process for Ankle

The ankle has multiple parts that each required different manufacturing. Starting with the baseplate, we used a stock .25” thick aluminum 6061 plate. This material was cut to size and the corners cut to the desired radius using a water jet. The clearance holes were drilled and countersunk to provide room for the bolt heads and create a flush surface.

The shell was cut from stock aluminum to the largest diameter of the shell. It was then contracted out to a shop technician to CNC the inner hole, outside curved edges, and shape the part. Then the mill was used to cut off the side material. The holes were then drilled using the drill press.

Figure 11: The Shell after CNC before milling the sides

The post that is captured by the rubber is composed of two parts. The cross was cut from stock sheet metal on the water jet in order to attain the desired shape. This piece was joined to the to the smaller diameter pylon by welding it to create the lower post assembly.

The two rubber parts require the most steps to create the final product. The first step was to use the 3D CAD and print the parts. The positive models of the part were used to create multi-use silicone molds. These molds were then used to form the rubber bushings. To form the rubber we use a two part liquid rubber and mold release so that our inserts can be easily removed.

Figure 12: The positive 3D upper rubber bushing

Figure 13: The silicone molds for the rubber bushings

Manufacturing Process for Carbon Fiber Foot

Laminae of carbon fiber will be cut from prepreg Uni-tape of TenCate carbon fiber sheets, Part Code: TC 275-1/HM63-12K-70. These sheets will be used to create a symmetric balanced laminate containing 26 unidirectional laminae. The prepreg is cut into rectangular lamine the using an exacto knife.

Figure 14: Cutting a lamina from the prepreg roll.

A lamina is heated with a heat gun to activate the adhesive resin on the surface. A second lamina is laid over the heated lamina and the lamina are pressed together using a squeegee to remove the air bubbles between the plies. This was repeated until the unidirectional laminate was constructed. Each ply was cut and laid in the correct fiber angle direction as shown in the analysis. A taper of the zero degree plies starts one inch beyond the baseplate and progresses in even increments until the end, leaving only 10 plies in the toes for more flexibility. The laminate was then cut into the shape of the foot using the exacto knife.

Figure 15: Using hands and the squeegee to remove air bubbles when layering the plies of the laminate.

On the curing plate, adhesive gum was shaped around the rectangular plate and a vacuum bag material was laid down. The mold made out of foam was then placed, slightly off center on the plate so there was room for a valve. The carbon fiber laminate was put on the mold with a piece of vacuum bag in between the mold and laminate to avoid the foot sticking to the mold. A small breather piece of fabric was placed with the bottom of the valve on top of it to allow air to escape. The top vacuum sheet was then placed on top and sealed with the gum tape.

After the layup was fitted snugly to the adhesive gum, a hole was cut in the bag where the vacuum valve was and the top half of the valve was put in place. To ensure the bag was leak-proof, a vacuum was pulled on the valve and the bag was checked for leaks.

When the check was complete, the curing plate was moved into the oven and hooked up to the vacuum hose inside. A preprogrammed curing cycle was loaded into the oven computer and the curing process began. A vacuum was pulled on the bag and a 2.5 hour long heat cycle cured the laminates at 265ºF. After the cycle was completed the curing plate was removed, the bag was ripped open, and the laminate inspected.

Figure 16: The autoclave computer controls running the curing cycle

After the composite was cured it was post processed by using a dremel with a carbon fiber vacuum filter. This removed any extra material and created a clean edge on the part.

To connect the foot to the rest of the assembly G Flex 650 liquid epoxy was used from Attachment D below. This is a two part epoxy that was mixed and applied to the bottom of the aluminum plate. The plate was sanded and cleaned to create a better bond. To avoid creating a galvanic cell the epoxy was thickly spread over the foot and the baseplate. This prevented and chance of the two materials contacting. It was set to cure under compression and cleaned up after it was fully cured.

Manufacturing Process for Posts

The upper post was cut from stock Aluminum 6061 material in lengths of 3.5”’, 4”, 6.5”, and 9.5”. The posts were turned down on the lathe to the correct outer diameter according to Appendix B. On the bottom of the post four 1 inch slots were cut on the mill to allow the bicycle clamp to hold the post in place.

The lower post was cut to length from stock material and also turned down on the lathe to the correct outer diameter according to the Appendix B drawing.

Difference in Manufacturing from Design

Our manufacturing process followed our design plan with few changes. One change was cutting 4 slots in the upper post so the clamp works and hold the post in place. The single slot in the original design was not enough. We also added another length of post with a 4 inch option because we had more material and it was easy to add while giving more length options to the users.

Recommendations for Future Manufacturing

For future manufacturing, it is recommend to CNC the shell part and make the wall thickness thinner. That will help reduce the weight of the assembly significantly, and it is not needed for structural integrity. Also, making the hole bigger in the shell would allow more movement and could be optimized for the athlete movement while still providing a hard stop to stop too much motion and the ankle from collapsing. The foot shape could be optimized as well for the particular participants size and flexibility depending on the specific user. Overall we believe it is a good shape for our target demographic.

Cost Estimate for Production

For future production it is recommended to have automated machinery to produce the metal parts of the prosthetic foot. This will help to decrease time of production as well as increase the efficiency and accuracy of the production of parts. Table 4 estimates the material cost per one prototype. The estimation of the active work time needed to produce the foot by one person is about 30 hour; this was done by approximating the time it took to produce each part. Using the amount of active work time to produce the surf leg, the cost of production per part is $619.50; using the average machine technician salary of $20.65 per hour [22]. The production cost is an overestimate of the actual production cost because it doesn't take into account multiple workers, or the ability to create an efficient workplace. For one person to mass produce the prosthetic foot, the cost per foot is $919.74 to produce.

Table 4: Cost Estimate for materials for a single prosthetic foot

#	Part	Material	Cost
1	Metal Plates	Al Sheet 12"x12"x .25"	$6.87
2	Metal Cover	Al Rectangular Bar 2"x4"x12"	$70.18
3	Standard-Wall Aluminum Pipe	Al Round Tube 1-5/16"x .25"x36"	$21.43
4	Thick-Wall Aluminum Unthreaded Pipe	Al Round Tube 1-¼" x 0.91" x 36"	$27.96
5	Bike Clamp	Al 7076	$9.36
6	Liquid Rubber	PT Flex 70 Liquid Rubber 4lb	$16.50
7	Female Pylon Adapter	Titanium Tube Clamp Adapter	$33.25
8	Pylon to Socket Adapter	Titanium 4 Hole Male Pyramid	$46.44
9	Epoxy	G/Flex Epoxy	$5.00
10	Connectors	6 x 1/4" Countersunk Bolt	$1.00
11	Connectors	6 x 1/4" Fly Wing Nut	$1.00
12	Rubber	PT Flex 85 Liquid Rubber	$16.50
13	Rubber	PT Flex 35 Liquid Rubber	$16.50

14	Rubber	PT FLex 45 Liquid Rubber	$16.50
15	Carbon Fiber	Carbon Fiber composite	$10.00
16	Water shoe	Rubber and neoprene	$11.75
		Total	$300.24

Design Verification (Testing)

Verification and Testing Plan

In order to verify that the prosthetic leg is safe to be used and meets the design requirements, the tests listed in Table 5 were performed. Table 5 shows the details of tests performed and the summarized results.

Table 5: Test Descriptions and Results

#	Test	Test Description	Results
1	Rubber Hardness	Test for choosing rubber hardness to provide required ankle movements. Volunteer tested 3 different pairs of rubber stiffnesses.	Provided ankle movements for squatting. The range of ankle movement was measured and compared for different stiffnesses.
2	Load Test	Test if the leg can support 300 lbf without deformation. The volunteer weight was 128 lb.	Was able to successfully support the volunteer without any mechanical issue.
3	Carbon Fiber Flexibility	Test the carbon fiber foot for bending. The carbon fiber foot was tested by multiple students stepping on the foot and applying their weight. The weight range was 120-250lbs.	The foot provided resistance when applied weight. The foot would expand as weight applied and comes back to normal position, providing some flexibility.
4	Durability	Test the overall assembly by twisting. The foot was clamped to the table and the post was twisted.	The bonding of the foot to metal plate was not secure in the first trial but it was securely bonded the second time.
5	Corrosion	Test the corrosion resistance of the prosthetic in salt water environment. The parts were placed in Salt and Fog Chamber for 40 days. The samples were weighed and the dimensions were measured before and after.	The metal parts had slight discoloration. The carbon fiber foot and the rubber parts did not show any significant change due to corrosion.

Rubber hardness test (1) was used to determine which rubber shore hardness would provide necessary ankle movements and resistance. Multiple rubbers with shore hardness range of 30A to 85A were made and tested by a volunteer. The volunteer who helped us to test the prototype was Karen Agdelott, who is a transtibial amputee. Karen is very active and she likes to swim, cycle and run. Although she doesn't surf, she was able to try on the prototype, squat and shift her weight from side to side as seen in the figure below.

Figure 17: Karen squatting with 44 upper and lower bushings pair

We tested 3 different pairs of upper and lower bushing pairs and measured the angles of ankle movements while she was squatting. The angles were measured using a protractor application. We have also evaluated the comfort and the resistivity of the rubber bushings from Karen's feedback. For her weight and height, which are 128lbs and 5'4" respectively, upper bushing with durometer of 44 was the most comfortable to move around and provided enough ankle movement range to squat. The 70 upper bushing provided more resistivity, but it was not as comfortable as 44 for ankle movement. The 30 upper bushing was concluded too soft because it was reaching the hard stop of the metal shell. The details of ankle movement range for each pair is recorded in Table 6.

Table 6: Data Table of Ankle Movement Range

Lower	Upper	Dorsiflex	Plantarflex	Eversion	Inversion
44	44	25-30°	18°	20°	20°
44	70	25°	10°	10°	12°
70	30	30+°	-	2-°	25°

By having a volunteer test the prototype and applying full body weight on the post, we have concluded that the prosthetic leg was able to withstand a weight of 128lbs. This was recorded as the result of static load test (2). For carbon fiber foot (3), several students with different weights stepped on it and applied their whole body weight on the foot before assembling the final prototype. The students had a weight range of 120-250lbs. We have concluded that the carbon fiber foot with 26 layers provided the flexibility that supports a wide range of weights applied. Once the prosthetic leg was assembled, the durability test (4) was performed to check the epoxy bond between the metal plate and the carbon fiber foot. We have clamped the foot on a table and twisted the post forward and backwards applying tension. This resulted in a small crack in the epoxy bond, but did not affect the carbon fiber layer or the metal plate. Then, we have changed the epoxy to flexy epoxy and assembled the parts again.

The corrosion test (6) was used to verify if the assembly could resist corrosion of sea water and air since the prosthetic would be exposed to both during surfing. The most realistic approach of testing corrosion was to use “Salt Fog Spray Chamber” as it provides the conditions of both salt water and air. Part samples were placed in the chamber for 40 days/ 960 hours with weekly monitoring and maintenance.

Figure 18: Samples Loaded in the Chamber

The test followed the ASTM B117-16 standard for operating the salt fog chamber [18]. The spray chamber was filled with 5% NaCl salt solution and the chamber conditions were set to 35°C for temperature and 47psi for pressure. Once the assembly was removed from the chamber, visual inspection and mass inspection were used to determine the corrosion rate. The samples are shown in the figures below.

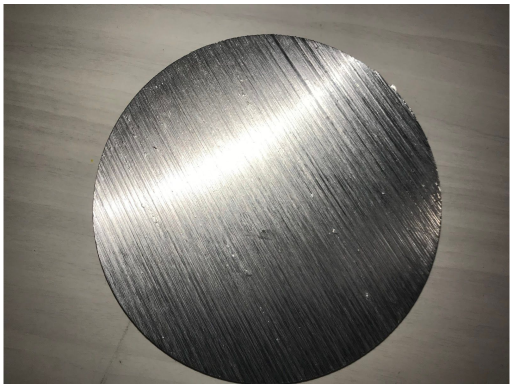


Figure 19: Sample 1- Al 6061 Solid Disk

Figure 20: Sample 2 - Al 6061 Tube

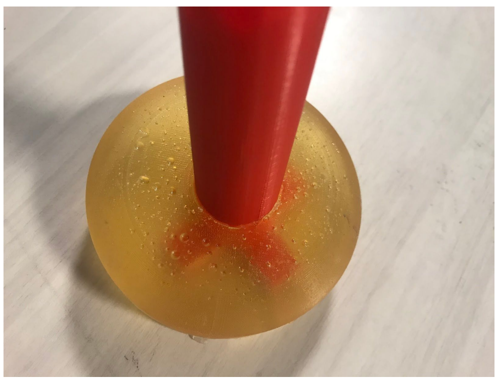


Figure 21: Sample 3 - 85 Rubber

Figure 22: Sample 4 - Carbon Fiber Foot

The samples were weighed and the dimensions were measured before placing them in the chamber. After the test period, the samples were weighed and measured again for comparison. The summary of sample weight, dimension and corrosion rate calculated are shown in Table 7.

Table 7: Data of Corrosion Rate

Sample #	Before		After		Corrosion Rate
	Dimensions	Weight	Dimensions	Weight	
1	diameter =6” Thickness =0.486”	654g	diameter=6” thickness=0.487”	652.1g	-0.002g/hr
2	Wall thickness= 0.075”, 0.115” diameter=1.21”, 1.281”, 1.26”	86g	Wall thickness =0.074”, 0.116” diameter=1.21”, 1.285”, 1.265”	85.8g	-0.0002g/hr
3	-	170g	-	174.4g	+0.0046g/hr
4	Length=12” Width=4”	100g	Length=12” Width=4”	102.5g	+0.0026g/hr

The corrosion test results showed that the carbon fiber foot (sample 4) was not affected by salt water in terms of flexibility or durability. The weight has increased at a rate of 0.0026g/hr as carbon fiber absorbs water. This does not affect the mechanical properties significantly. The Al parts showed slight discoloration with a corrosion rate of 0.0002- 0.002g/hr. This is expected as Al oxides with the presence of salt water and air. However, with proper maintenance such as cleaning with tap water after surfing, would help prevent corroding of Al parts. The rubber part (sample 3) had weight increase at a rate of 0.0046 g/hr due to water absorption. From visual inspection, the sample didn’t show any significant change. The limitations of the test that we have not tested the assembly. If Al is bonded to carbon fiber (composite) directly, it is expected to increase the corrosion rate of the metal due to electron potential. We weren’t able to determine the corrosion rate for the whole assembly. Thus, if the corrosion rate for the assembly was significantly high, fiber glass could be used between the composite and metal to prevent that.

The tests in Table 5 would be utilized to verify that the product meets the customer requirements and the engineering specifications set in the beginning of the project as listed in Table 1. To confirm that all the specifications are met, specification verification checklist is shown in Table 8. Besides testing, specifications such as weight and friction were inspected through different methods. The weight requirement was met by weighing the assembly. The friction on board requirement was met by utilizing a surfing bootie and physically inspecting the friction of the sole on surfboard. The target values for each specification were set as the acceptance criteria for each test and inspection method. The number of tests performed is also included in Table 6 along with the type of verification. Type A is concept verification, type B is design verification and type C is product validation.

Table 8: Specification Verification Checklist

#	Specification	Test/Inspection Method	Target	SAMPLES TESTED	
				Quantity	Type
1	Antirust	Corrosion Test	Minimal Corrosion	1	C
2	Bending Deflection	Carbon Fiber Foot	0.1 ± 0.1 in deflection	10	B
3	Buckling	Load Test	300 ± 5 lbf	1	B
4	Weight	Weigh the assembly	<4lbs	2	C
5	Friction on Board	Use surfing bootie	0.5 ± 0.2 No slipping	1	C
6	Dorsiflexion	Rubber Hardness Test	30 ± 10	1	A
7	Plantar Flexion	Rubber Hardness Test	30 ± 5	1	A
8	Pronation	Rubber Hardness Test	15 ± 2	1	A
9	Eversion	Rubber Hardness Test	10 ± 2	1	A
10	Sealed Bearing	Durability Test	No breaking apart	1	C
11	Degrees of Rotation	Rubber Hardness Test	3	1	B
12	Joint Torsion Stiffness	Inspected through twisting	40 ± 10 psi	2	B

In order to verify that the weight of the prosthetic leg is less than 4lbs/ 1.81kg, each part was weighed as shown in Table 9 and Table 10. Depending on which rubber bushings and post the user decides to use, the weight ranges from 1.4513 - 1.6237kg.

Table 9: Weight Data of Non Replaceable Parts

Part	Mass (grams)
Metal Cap	312.6
Base Plate	179.6
Lower Post	103.4
Bike Clamp	56.1
4 screw adapter	146.9
Pyramid adapter	70
Foot Model #1	126.1
Foot Model #4	108.5
6x Bolts and screws	67.6

Table 10: Weight Data of Replaceable Parts

Pylon Length (inches)	Mass (grams)		Shore Hardness	Lower Bushing Mass (g)	Upper Bushing Mass (g)
4”	110.2		30	135.8	147.5
5.2”	144.9		44A	135.4	143.4
6.5”	180		70	139.6	146.4
9.3”	260.1		85	145.5	155

Conclusions and Recommendations

In conclusion, the goal of this project was to design and manufacture a multi-user transtibial prosthetic leg for surfing. The project was sponsored by the QL+ organization and benefits Operation Surf to help veterans with transtibial amputee to surf with comfort. Our team has designed a prosthetic leg that meets the customer requirements and the design specifications, which were developed through meeting with the customer and researching surfing biomechanics.

The final design consists of four components: ankle, foot, post, and the adapter. The most important requirement, the ankle movement for squatting during surfing, was met by incorporating rubber into the design to provide flexibility in ankle motions. The rubber parts come with 4 different types of stiffness that the user can choose from depending on their weight. The foot design was focused on providing flexibility to balance and flex. The post was designed to fit multiple users with different heights ranging from 4’11” to 6’6”. The adapter was chosen to fit different sockets.

Our team has followed detailed manufacturing plan for each component with some alterations along the process. The manufacturing process included making the carbon fiber foot in the composites lab, making silicone molds of the rubber bushings and casting the rubber parts, and machining the Al tubes and solid disk to desired shapes and dimensions at the machine shops. Then the components were assembled using screws, bike clamp and epoxy.

In order to validate the design mechanical and material tests were performed. The mechanical tests did not include any testing machine due to time constraints of the project. The mechanical tests were mainly tested through volunteers. We have invited a volunteer to test the prototype and validated the functionality of the design. The prosthetic leg provided the ankle flexibility needed for squatting, was lightweight and comfortable. For material testing, corrosion testing on some parts’ materials was performed using Salt Fog Chamber at the Civil Engineering lab.

One of the recommendations for the project would be to start with detailed reference sizes for dimensioning the design. This would make the process of prototyping easier and ensure that the prosthetic leg is properly dimensioned to fit the user. Another recommendation would be to use testing machine for rubber wearability and obtain accurate data for the wearability of the rubber, so the user can estimate when to change the rubber components.

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Our advisor Jim Widmann helped guide us in weekly meeting and keep us on track with our project. We discussed our ideas and used his guidance to finish our project.

Thank you to Pat and Dennis for filming us through our design, manufacturing, and testing process. They made great videos for the College of Engineering that portrayed our challenge and project progression.

Karen helped us test the leg and was the first transtibial amputee to wear our design. She provided us positive feedback and help us understand the movement we were able to achieve in the prosthetic.

Dr. Elghandour for letting us use his Salt Fog Spray Chamber for corrosion testing and Anthony for helping us set up the chamber.

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Appendices

A. **QFD and Matrices**

B. **Final Drawings**

C. **List of vendors, contact information, and pricing**

D. **Vendor supplied component specifications and data sheets**

E. **Detailed supporting analysis**

F. **Gantt Chart**

G. **Safety Checklist**

H. **User guide for the prosthetic Leg**

Appendix A: QFD and Decision Matrices

Table 1: Quality Function Development Table

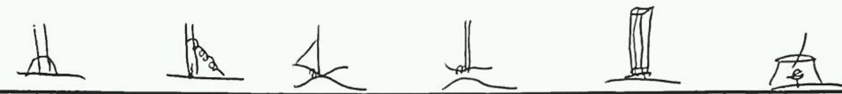
Customer (Step #1) Requirements (Whats) / Customer Requirements (Step #2)	Weighting (1 to 5)	Antirust, resist corrosion	Bending deflection	Buckling	weight	Friction on board	Dorsiflexion	Plantar Flexion	pronation	eversion	Torsion	Wetsuit and prosthetic on at same time	Sealed Bearing	Degrees of Rotation	Torsion Stiffness in joint						Benchmarks: Ossur	Benchmarks: Adaptive sportsankle
Waterproof	5	9																			*	*
Knee bending	3		1	1		3								9	9							
Traction on board	5					9																
Easy to balance	3		1	1		3	3	3	9	9	1			9	9						*	*
Ability to control the board	4		9	9	3	9	9	9						9								*
Prosthetic doesn't fall off	5					3						1									*	
Light weight	3	1			9								1								*	
Ankle mobility	5						9	9			3			3								*
Comfortable to wear	5				3							3	3									
Survive in sand	3	9											3								*	*
Wet suit integration	2											9	3									
not hinder paddling	2				9							3	9									
Units		mm/year	in	lbf	lbs		degrees	degrees	degrees	degrees	psi	'	cycles	degrees	psi							
Targets		0	0.1	60	4	0.6	50	30	15	10			10,(									
Benchmark #1																						
Benchmark #2																						
Importance Scoring		75	42	42	72	114	90	90	27	27	18	44	51	105	54	0	0	0	0	0		
Importance Rating (%)		66	37	37	63	100	79	79	24	24	16	39	45	92	47	0	0	0	0	0		

Engineering Requirements (HOWS)

● = 9 Srong Correlation

○ = 3 Medium Correlation

Δ = 1 Small Correlation



	Concepts					
Criteria	Lacross Ball	All spring design	Dual compression no pinch	Dual compression pinch	two way pinch	Rubber with U-joint
Return strength in the flexion direction	D	1	1	1	1	1
Return strength in the rolling direction	D	1	1	1	1	1
Return strength in twisitng	D	-1	-1	-1	-1	0
Range of motion in the flexion	D	1	2	1	1	1
Range of motion in the rolling direction	D	1	1	1	1	1
Range of motion of a twist	D	-1	-1	-1	-1	1
Control of motion in twist	D	0	0	0	0	0
Size of ankle joint	D	-1	-1	-1	0	0
Predicted strength	D	1	0	1	0	-1
Durability	D	0	-1	0	1	-1
Ease of changing a post	D	-1	-1	-2	-2	1
Ease of change resistance	D	0	1	1	0	1
Likely to break	D	0	-1	0	0	-1
	0	1	0	1	1	4

Figure 1: A pugh matrix analyzing ankle and foot designs

Universal Adaptor					
Criteria/concept	Sleeve over Socket	Magnetic sleeve over socket	4 hole configuration to female-male pyramid connecter	female-male pyramid connector to 4 screw	hip harness
ease of connecting	+	+	D	S	-
alignment ability	-	s	D	S	-
stability	-	-	D	S	-
comfort	S	S	D	S	-
ease to congifure to desing	-	S	D	S	-
similarity to whats already used	-	-	D	S	-
Sum +	1	1		0	0
Sum -	4	2		0	6
Sum S	1	3		6	0

Figure 2: Pugh matrix on the universal adapter

Foot							
Criteria\Concept	Flat Carbon/epoxy	Split toe	Rubber outsole	Double layered	Curved U shape	Curved n shape	X shape
Flexibility	D	+	+	+	-	+	+
Return to Position		-	-	+	+	+	+
Bend	A	+	+	+	-	+	S
Traction		+	+	S	-	S	+
Stability	T	+	+	S	-	+	+
Lightweight		S	-	-	S	S	S
Material Degredation	U	S	-	S	S	S	S
Dorsiflextion		S	+	+	+	+	+
Plantar Flexion	M	S	+	+	+	+	+
Eversion		+	+	S	-	-	+
Inversion		+	+	S	-	-	+
Sum +		6	8	5	3	6	8
Sum -		1	3	1	6	2	0
Sum S		4	0	5	2	3	3

Figure 3: Pugh Matrix on the foot motion

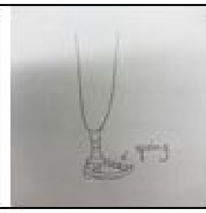
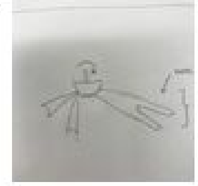
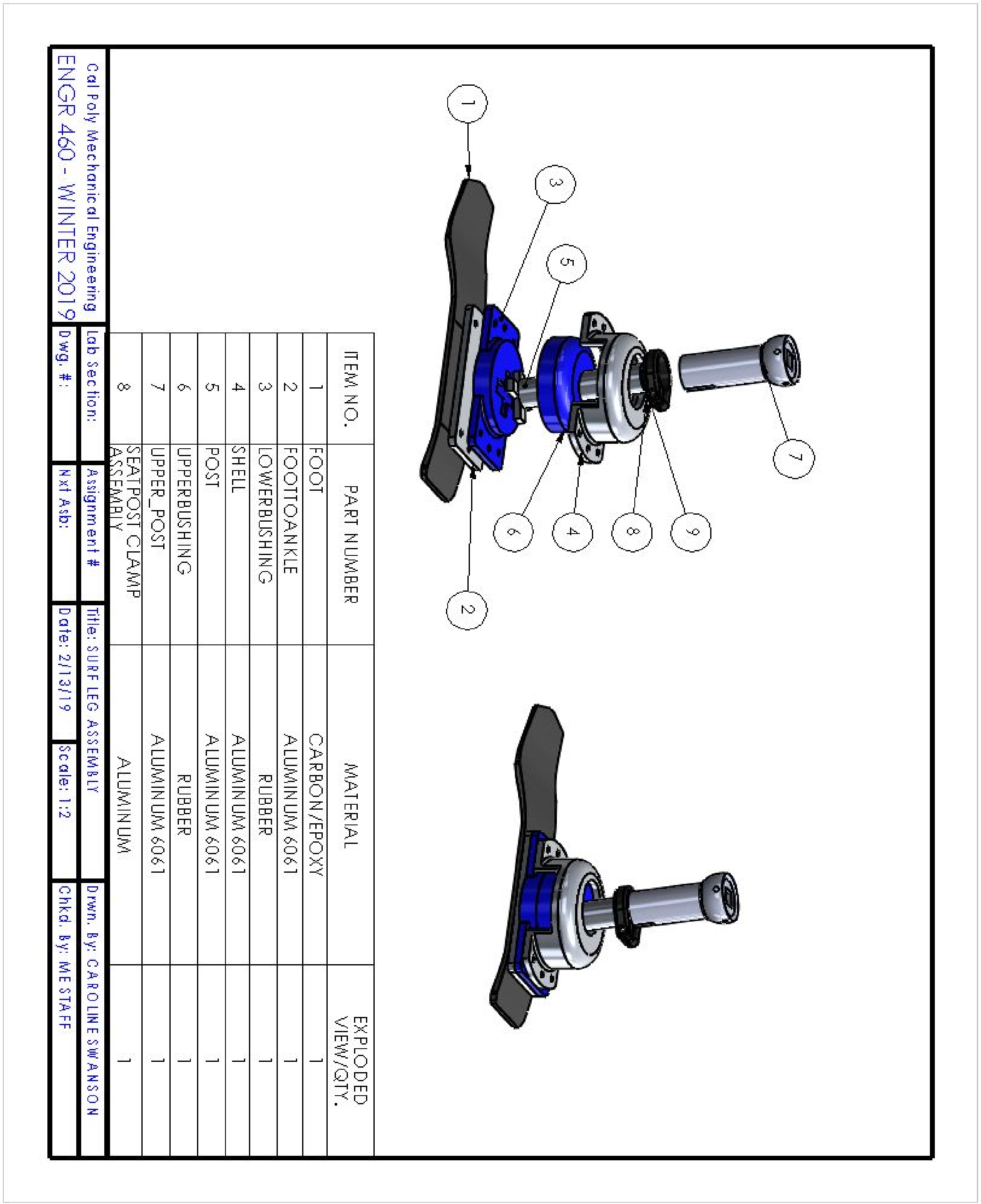
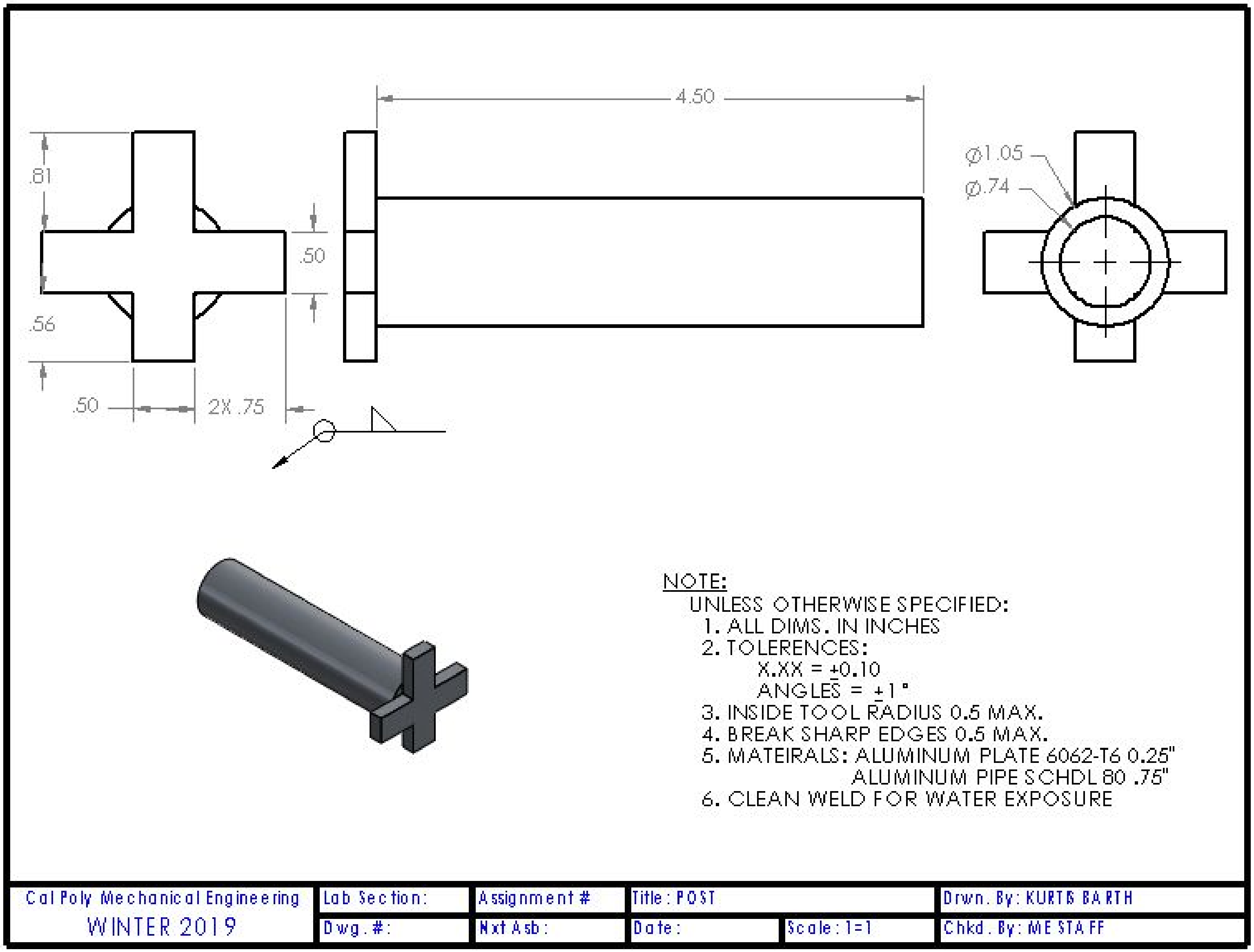
Criteria/Concept					
	1 (Pro flex)	2 (Spring with Curved toes)	3 (Rubber and split toe)	4 (Piston with flat toes)	5 (Rubber with X shaped foot)
Corrosion resistance	D	-	+	-	+
Pronation	A	S	+	S	+
Plantar/Dorsiflexion	T	+	+	+	-
Light Weight	U	+	+	S	+
Balance	M	-	S	-	+
Friction		S	S	S	-
∑+		2	4	1	4
∑-		2	0	2	2
∑S		3	2	3	0

Figure 4: Pugh matrix on the foot shape

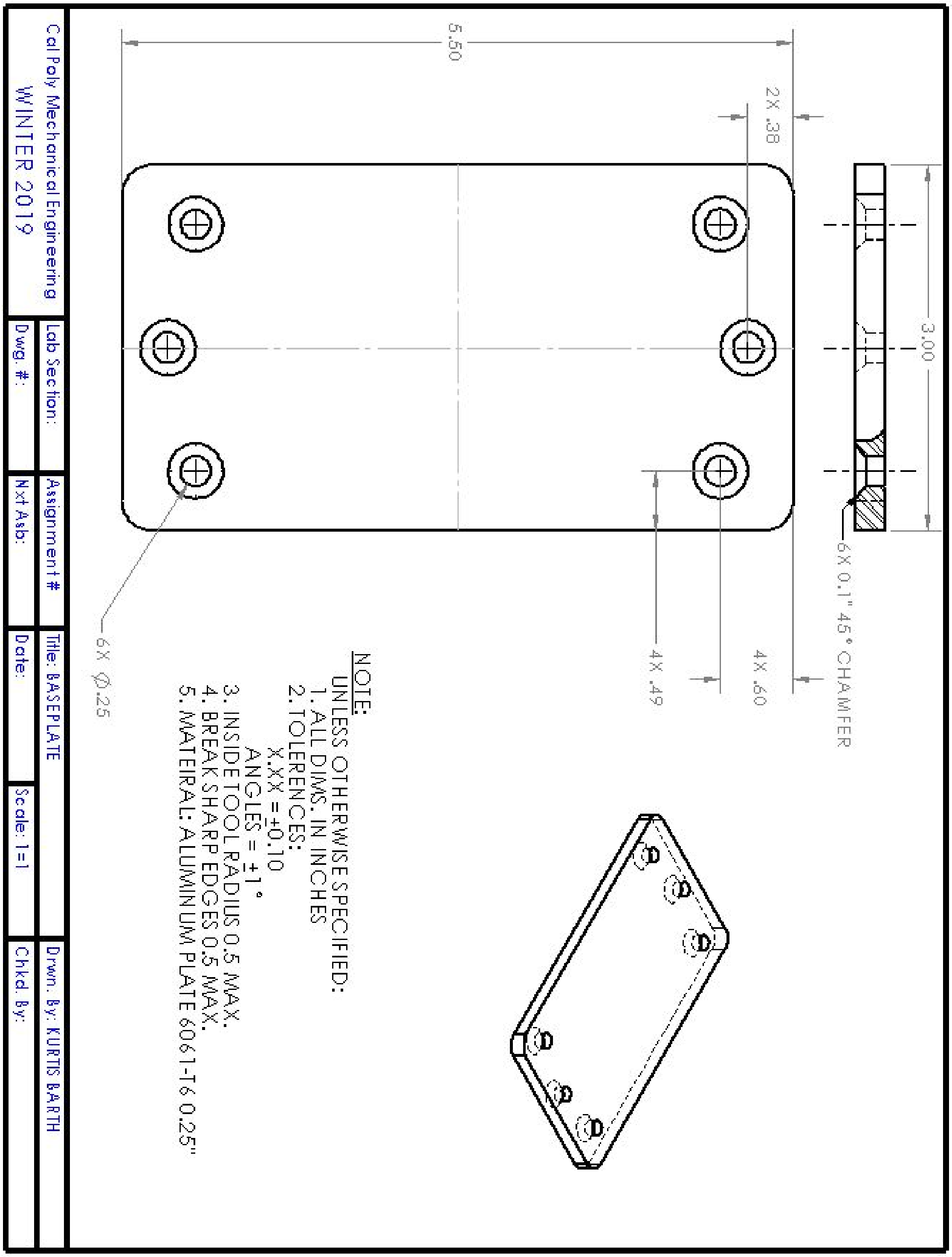
Appendix B: Final Drawings

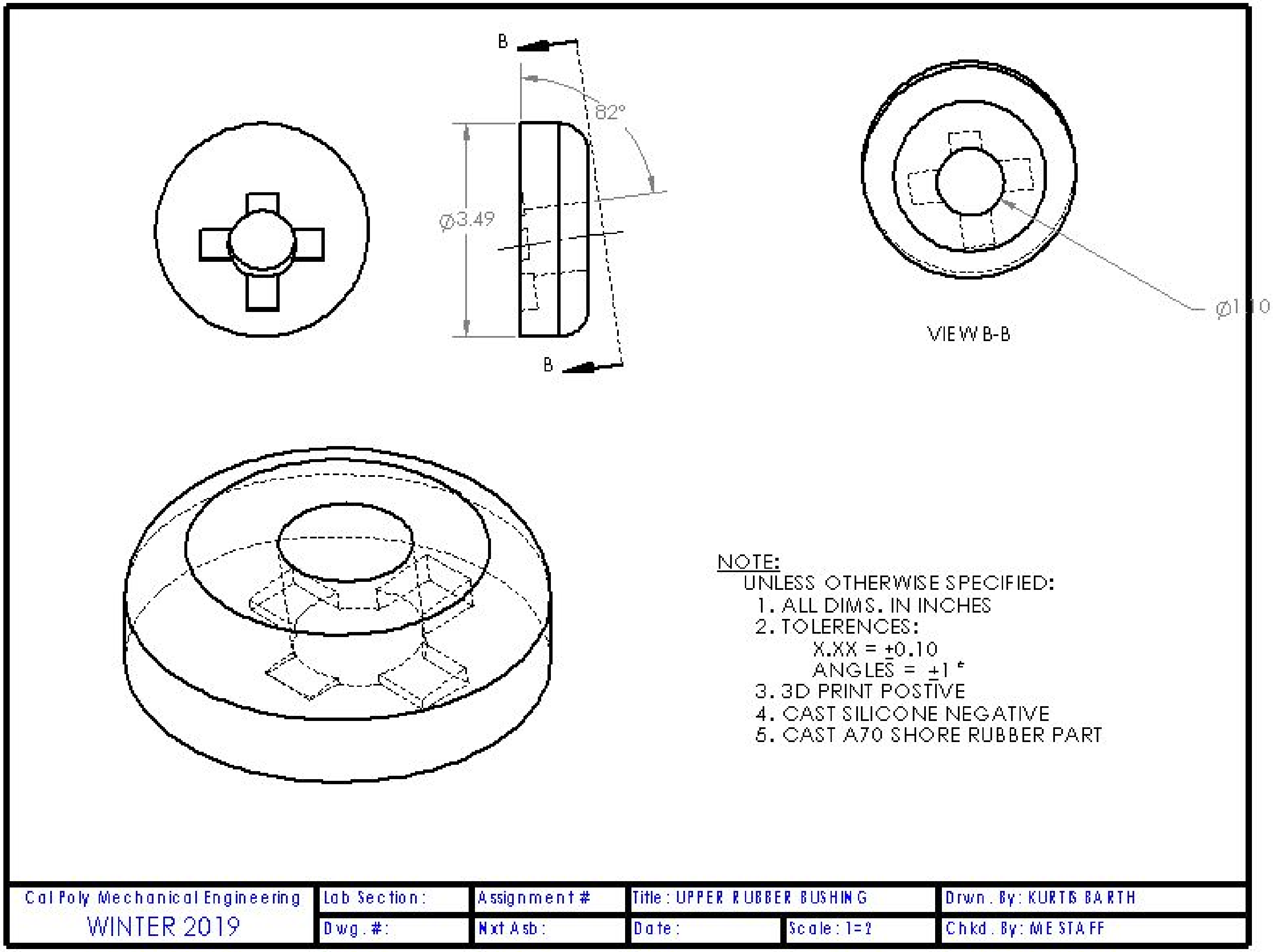


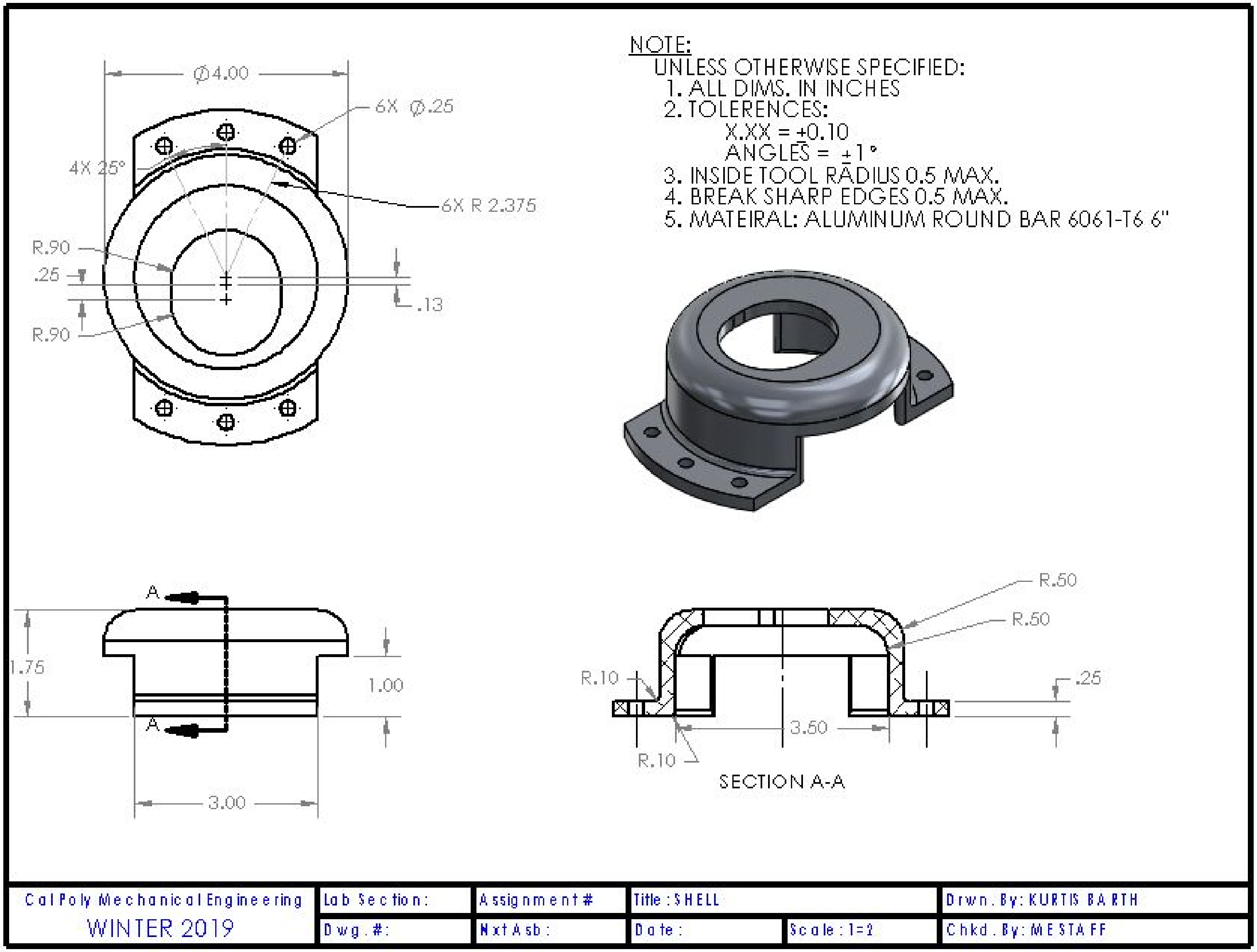
ITEM NO.	PART NUMBER	MATERIAL	EXPLODED VIEW/QTY.
1	FOOT	CARBON/EPOXY	1
2	FOOTTOANKLE	ALUMINUM 6061	1
3	LOWERBUSHING	RUBBER	1
4	SHELL	ALUMINUM 6061	1
5	POST	ALUMINUM 6061	1
6	UPPERBUSHING	RUBBER	1
7	UPPER_POST	ALUMINUM 6061	1
8	SEATPOST CLAMP ASSEMBLY	ALUMINUM	1



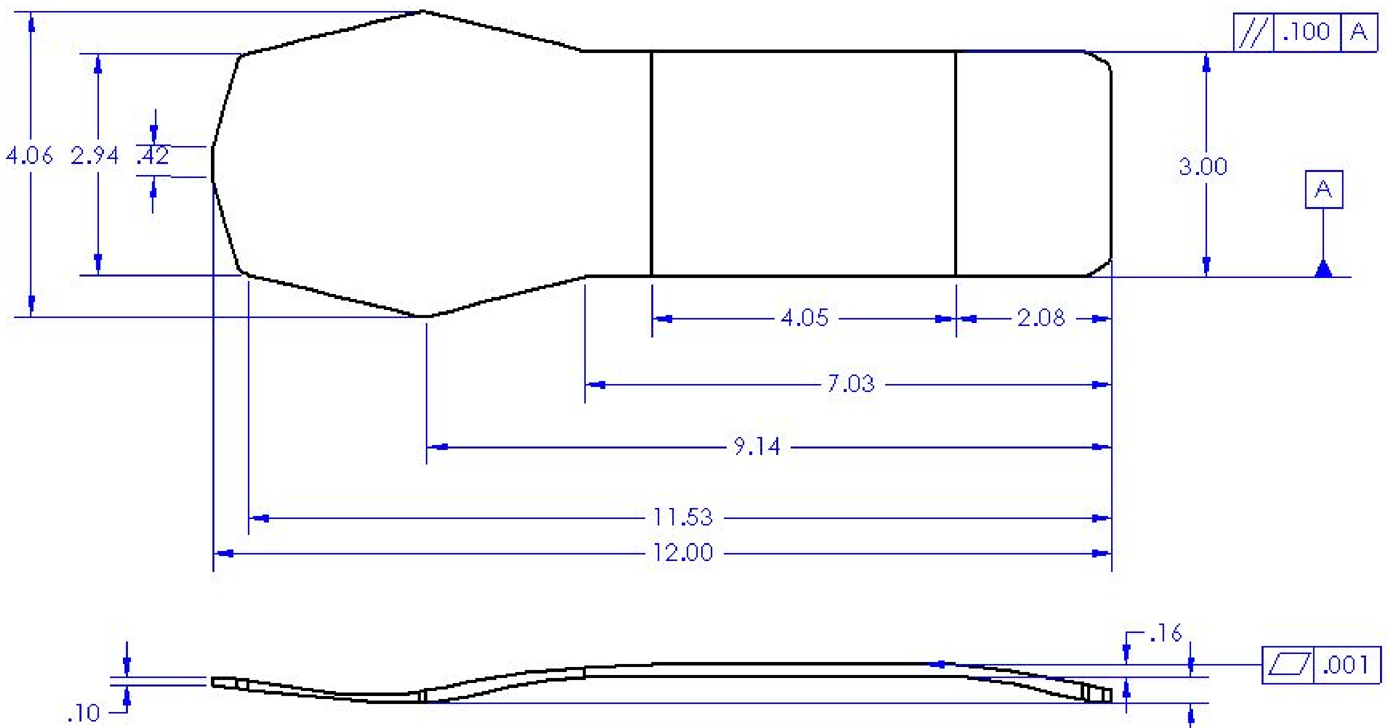
4.50
.81
.56
.50
.50
2X .75
Ø1.05
Ø.74
NOTE:
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERENCES:
X.XX = ±0.10
ANGLES = ±1°
3. INSIDE TOOL RADIUS 0.5 MAX.
4. BREAK SHARP EDGES 0.5 MAX.
5. MATEIRALS: ALUMINUM PLATE 6062-T6 0.25"
ALUMINUM PIPE SCHDL 80 .75"
6. CLEAN WELD FOR WATER EXPOSURE
Cal Poly Mechanical Engineering
WINTER 2019
Lab Section:
Dwg. #:
Assignment #
Nxt Asb:
Title: POST
Date:
Scale: 1=1
Drwn. By: KURTIS BARTH
Chkd. By: ME STAFF


5.50
2X .38
3.00
6X 0.1" 45° CHAMFER
4X .60
4X .49
6X ⌀.25
NOTE:
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERENCES:
X.XX = ±0.10
ANGLES = ±1°
3. INSIDE TOOL RADIUS 0.5 MAX.
4. BREAK SHARP EDGES 0.5 MAX.
5. MATERIAL: ALUMINUM PLATE 6061-T6 0.25"
Cal Poly Mechanical Engineering
WINTER 2019
Lab Section:
Dwg. #:
Assignment #
Nxt Asb:
Title: BASEPLATE
Date:
Scale: 1=1
Drwn. By: KURTIS BARTH
Chkd. By:

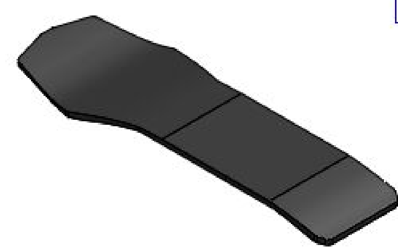

B
82°
Ø3.49
B
VIEW B-B
Ø1.10
NOTE:
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERENCES:
X.XX = ±0.10
ANGLES = ±1°
3. 3D PRINT POSTIVE
4. CAST SILICONE NEGATIVE
5. CAST A70 SHORE RUBBER PART
Cal Poly Mechanical Engineering
WINTER 2019
Lab Section:
Dwg. #:
Assignment #
Nxt Asb:
Title: UPPER RUBBER BUSHING
Date:
Scale: 1=2
Drwn. By: KURTIS BARTH
Chkd. By: ME STAFF



Ø4.00
6X Ø.25
4X 25°
6X R 2.375
R.90
.25
R.90
.13
NOTE:
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERENCES:
X.XX = ±0.10
ANGLES = ±1°
3. INSIDE TOOL RADIUS 0.5 MAX.
4. BREAK SHARP EDGES 0.5 MAX.
5. MATEIRAL: ALUMINUM ROUND BAR 6061-T6 6"
A
A
1.75
1.00
3.00
R.50
R.50
R.10
.25
3.50
R.10
SECTION A-A
Cal Poly Mechanical Engineering
WINTER 2019
Lab Section:
Dwg.#:
Assignment#
Nxt Asb:
Title: SHELL
Date:
Scale: 1=2
Drwn. By: KURTIS BARTH
Chkd. By: ME STAFF



NOTE:
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERENCES:
X.XX = ±0.10
ANGLES = ±1 °
3. INSIDE TOOL RADIUS 0.5 MAX.
4. BREAK SHARP EDGES 0.5 MAX.
5. MATEIRAL: CARBON/EPOXY



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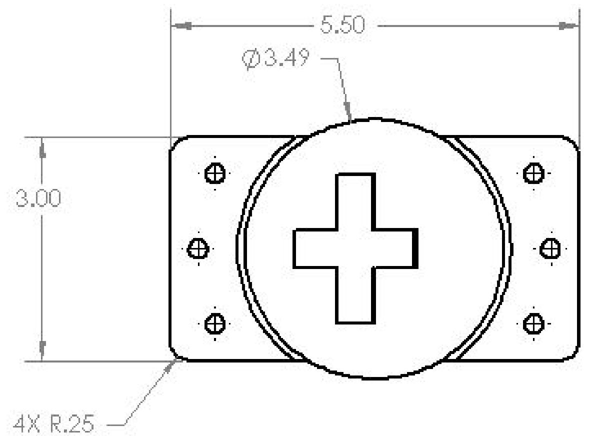
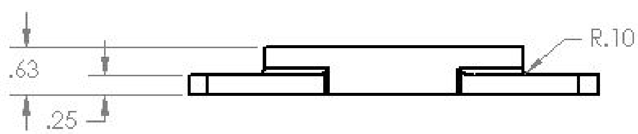
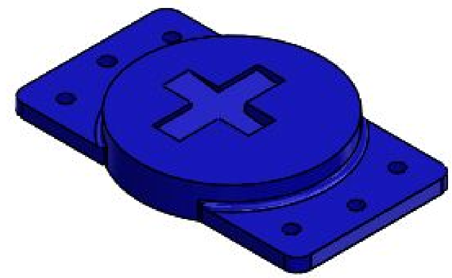
ENGR 460 - WINTER 2019	Dwg. #: 1	Nxt Asb:	Date: 2/12/19	Scale:1:2	Chkd. By: ME STAFF

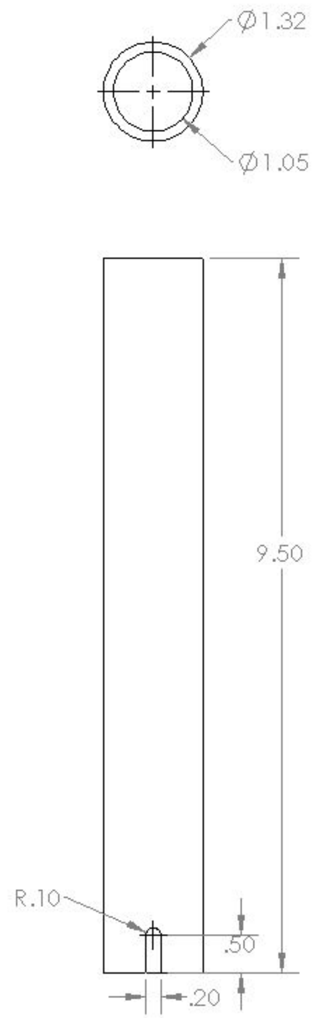


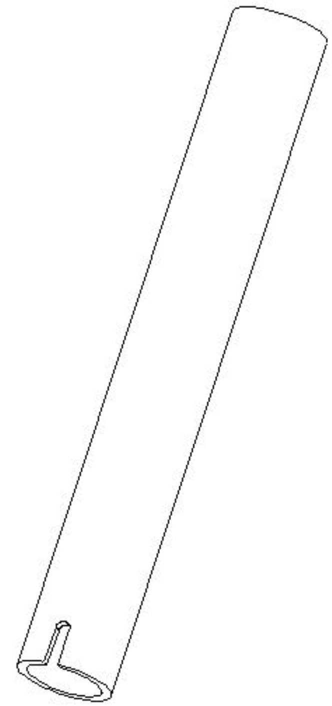




NOTE:
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERENCES:
X.XX = ±0.10
ANGLES = ±1 °
3. 3D PRINT POSTIVE
4. CAST SILICONE NEGATIVE
5. CAST A70 SHORE RUBBER PART

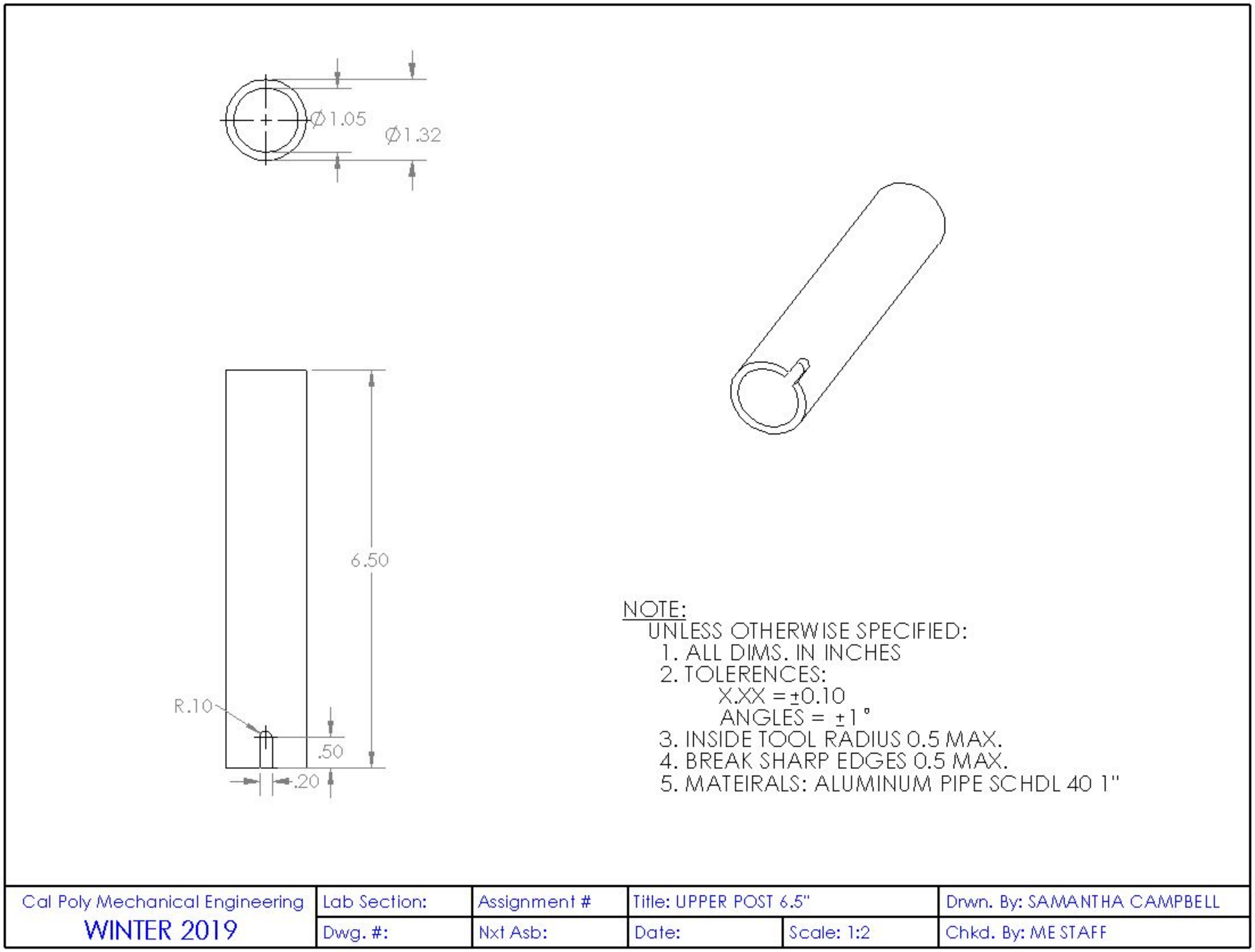
Cal Poly Mechanical Engineering	Lab Section:	Assignment #	Title: LOWER BUSHING		Drwn. By: KURTIS BARTH
WINTER 2019	Dwg. #:	Nxt Asb:	Date:	Scale: 1=2	Chkd. By: ME STAFF

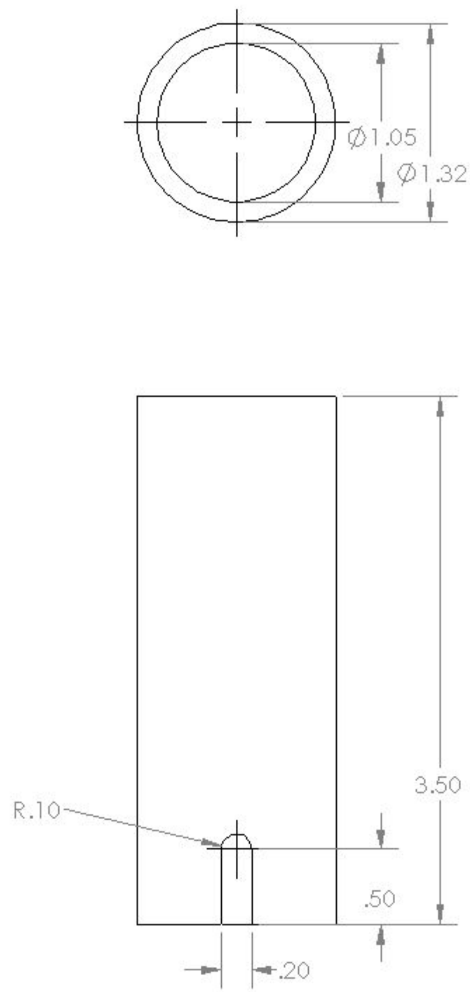


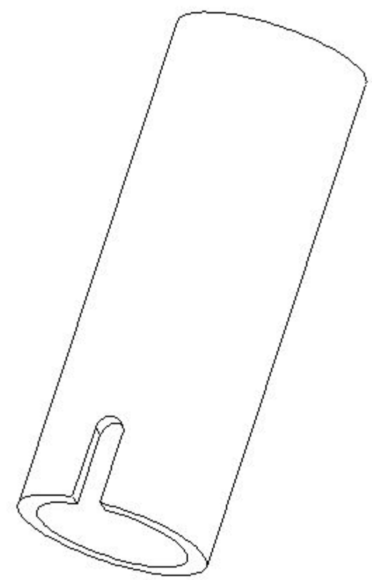


NOTE:
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERENCES:
X.XX = ±0.10
ANGLES = ±1 °
3. INSIDE TOOL RADIUS 0.5 MAX.
4. BREAK SHARP EDGES 0.5 MAX.
5. MATEIRALS: ALUMINUM PIPE SCHDL 40 1"

Cal Poly Mechanical Engineering	Lab Section:	Assignment #	Title: UPPER POST 9.5"		Drwn. By: SAMANTHA CAMPBELL
WINTER 2019	Dwg. #:	Nxt Asb:	Date:	Scale: 1:2	Chkd. By: ME STAFF


Ø1.05
Ø1.32
6.50
R.10
.50
.20
NOTE:
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERENCES:
X.XX = ±0.10
ANGLES = ±1°
3. INSIDE TOOL RADIUS 0.5 MAX.
4. BREAK SHARP EDGES 0.5 MAX.
5. MATEIRALS: ALUMINUM PIPE SCHDL 40 1"
Cal Poly Mechanical Engineering
WINTER 2019
Lab Section:
Dwg. #:
Assignment #
Nxt Asb:
Title: UPPER POST 6.5"
Date:
Scale: 1:2
Drwn. By: SAMANTHA CAMPBELL
Chkd. By: ME STAFF





NOTE:
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERENCES:
X.XX = ±0.10
ANGLES = ±1 °
3. INSIDE TOOL RADIUS 0.5 MAX.
4. BREAK SHARP EDGES 0.5 MAX.
5. MATEIRALS: ALUMINUM PIPE SCHDL 40 1"

Cal Poly Mechanical Engineering WINTER 2019	Lab Section:	Assignment #	Title: Upper post 3.5"		Drwn. By: Samantha Campbell
	Dwg. #:	Nxt Asb:	Date:	Scale: 1:1	Chkd. By: ME STAFF

Appendix C: List of vendors, contact information, and pricing

Description	Part number	Size	QTY	Price EA	Price EXT	URL
PT Flex 85 Liquid Rubber	N/A	4lbs	1	66	66	https://www.polytek.com/products/pt-flex-85-liquid-rubber
PT Flex 70 Liquid Rubber	N/A	4lbs	1	66	66	https://www.polytek.com/products/pt-flex-70-liquid-rubber
G/Flex Epoxy	n/a	4.5 Ounces	1	20	20	https://www.amazon.com/West-System-6508-Epoxy-Bottles/dp/B004QXPNH2/ref=sr_1_2?keywords=gflex+epoxy&qid=1559865805&s=apparel&sr=8-2
Ultimaker NFC PLA - Blue	n/a	.75kg, 2.85mm	1	49.95	49.95	https://www.dynamism.com/filament/ultimaker-pla.shtml
MAX Mold 20	n/a	Trial Unit	2	27.25	54.5	https://shop.smooth-on.com/mold-max-20
Universal Mold Release	n/a	12 oz can	1	13.94	13.94	https://shop.smooth-on.com/universal-mold-release
Standard-Wall Aluminum Pipe	5038K56	3 feet	1	42.68	42.86	https://www.mcmaster.com/5038k21
Thick-Wall Aluminum Unthreaded Pipe	4559T412	3 feet	1	55.91	55.91	https://www.dynamism.com/filament/ultimaker-pla.shtml
40 MM Titanium Tube Clam Adaptor	TCA/STCA-402-ADAPTOR	n/a	1	98.88	98.88	https://www.spsco.com/40-mm-tube-clamp-adapter.html
40 mm Bike seat clamp	silver	n/a	1	9.36	9.36	https://shop.smooth-on.com/universal-mold-release
Aluminum Round Bar 6061-T6	R616T651ND	12"	1	280.71	280.71	https://store.buymetal.com/aluminum/round-bar/6061-t6-t651/aluminum-round-bar-6061-t6-t651-6.html
Aluminum Plate 6061-T6\T6	P61.25T651ND	12" x 12"	1	27.28	27.28	https://store.buymetal.com/aluminum/sheet-plate/6061-t6-t651/aluminum-plate-6061-t6-t651-0.25.html

51						
Sodium Chloride (Crystalline Certified ACS)	**n/a**	**1 kg**	**1**	**87**	**87**	**Fisher Science**
4-Hole Male - Tough Dog Series	**TD-P21**	**70g**	**1**	**45**	**45**	**http://www.bulldogtools.com/prosthetic/four-hole-male-rated-for-350-lb_p_6308.html?osCsid=78597ab05939577410d345ce54dcf093**
surf shoe	**n/a**	**19**	**1**	**29.95**	**29.95**	**https://www.amazon.com/gp/product/B00IU2VB6W/ref=ppx_yo_dt_b_asin_title_o01_s01?ie=UTF8&psc=1**

total	**$947.34**

Appendix D: Vendor supplied component specifications and data sheets

Polytek Rubber Spec Sheet

Polytek
Development Corp.

Physical Properties of Poly PT Series Liquid Plastics & Rubbers

Product	PT Flex 20	PT Flex 50	PT Flex 60	PT Flex 70	PT Flex 85
Mix Ratio By Weight (By Volume)	1A:1B (1A:1B)	1A:1B (1A:1B)	1A:1B (1A:1B)	1A:1B (1A:1B)	1A:1B (100A:97B)
Part A Color	Clear Yellow	Clear Yellow	Clear Yellow	Clear Yellow	Clear Yellow
Part B Color	Opaque Tan	Clear Yellow/Amber	Clear Yellow/Amber	Clear Yellow/Amber	Clear Yellow/Amber
Mix Viscosity, cP	520	550	625	680	1600
Pot Life, min	5	8	5	5	5
Demold Time (hr)	0.5 @ 158°F 1½ @ 78°F	0.5 @ 158°F 1 @ 78°F	0.5 @ 158°F 1 @ 78 °F	0.5 @ 158°F 1 @ 78°F	0.5 @ 158°F 1 @ 78°F
Total Cure Time	7 Days @ 78°F 16 hr @ 140°F	7 Days @ 78°F 16 hr @ 140°F	7 Days @ 78°F 16 hr @ 140°F	7 Days @ 78°F 16 hr @ 140°F	7 Days @ 78°F 16 hr @ 140°F
Linear Shrinkage*	0.0050	0.0020	0.0026	0.0041	0.0013
Specific Gravity	1.00	1.03	1.03	1.05	1.06
Shore Hardness	A20	A50	A60	A70	A85
Tensile Strength, psi (MPa)	250 (1.72)	250 (1.72)	345 (2.38)	730 (5.03)	1064 (7.34)
Elastic Modulus, psi (MPa)	85	160	190	915	2700
Die C Tear Strength, pli (kN/m)	50 (8.8)	50 (8.8)	70 (12.3)	130 (22.8)	190 (33.2)
% Elongation	770	200	235	175	250

* Shrinkage is primarily caused by gelling while hot then cooling. Parts that cure with minimal temperature rise exhibit minimal shrinkage. Reported shrinkage is inch/inch.

Conventions: °C = (°F -32) x 0.57
psi/145 = MPa (megaPascals)
pli x .1751 = kN/m (kiloNewtons per meter)
NA = Not Applicable

Jan. 7, 2008: Supersedes Sept. 13, 2007
\Polytekbdc\cynthia\Physical Properties\PT Series.DOC

Carbon/Epoxy TenCate Spec Sheet

PRODUCT DATA SHEET

TENCATE

TENCATE ADVANCED COMPOSITES

TC250 Resin System

PRODUCT TYPE
265°F (130°C) Cure
Toughened Epoxy Resin System

TYPICAL APPLICATIONS
- Aircraft Structures
- Space Structures
- Radomes and Antennae
- Reflectors

SHELF LIFE
Tack Life
45 days at 75°F (24°C)

Out Life
60 days at 75°F (24°C)

Frozen Storage Life
12 months at <0°F (-18°C)

Tack life is the time during which the prepreg retains enough tack, drape and handling for easy component lay-up.

Out life is the maximum time allowed at room temperature before cure.

PRODUCT DESCRIPTION

TC250 offers an excellent balance of toughness, mechanical property translation and hot/wet performance and is easily processed via vacuum bag/oven, autoclave, or press curing operations. Although TC250 is a 265°F (130°C) cure system, it develops very high dry and wet Tg values which enhance the product's elevated temperature performance. TC250 can also be cured or free standing post cured to 350°F (177°C) to increase its high temperature performance.

TC250 is available with virtually all fiber reinforcements in unidirectional tape, slit unidirectional tape, woven and nonwoven prepreg formats.

PRODUCT BENEFITS/FEATURES

- Excellent mechanical property translation
- Can be initially cured at 180°F (82°C) and post cured free standing to 265°F (130°C) or 350°F (177°C) for prototyping with low cost tooling
- Good toughness
- Good surfacing properties
- Low laminate void content with low pressure vacuum curing
- NCAMP tested
- Easy processing
- Self-adhesive to core

NEAT RESIN PHYSICAL PROPERTIES

Density .... 1.21 g/cc
Dry Tg .... 285°F (140°C) cured at 265°F (130°C)
Wet Tg .... 257°F (125°C) cured at 265°F (130°C)

Dry Tg .... 356°F (180°C) post cured at 350°F (177°C)
Gel Time .... 6-10 min. at 265°F (130°C)

ELECTRICAL PROPERTIES OF COMPOSITE LAMINATES

TC250 / 4581 Quartz	C / X Band 8 - 18 GHz	Ku / K Band 18 - 26.5 GHz	Ka Band 26.5 - 40 GHz	Q & U Band 40 - 60 GHz
Dielectric Constant	3.47	3.43	3.42	3.40
Loss Tangent	0.015	0.015	0.011	0.012

TC250 / 7781 Fg	C / X Band 8 - 18 GHz	Ku / K Band 18 - 26.5 GHz	Ka Band 26.5 - 40 GHz	Q & U Band 40 - 60 GHz
Dielectric Constant	4.73	4.63	4.64	4.59
Loss Tangent	0.026	0.023	0.016	0.019

TENCATE

TENCATE ADVANCED COMPOSITES

TC250 Resin System

STANDARD MODULUS UNITAPE LAMINATE PROPERTIES

Laminate data used UD Tape Prepreg Laminate - HTS-40 12k Carbon Fiber, 150 gsm FAW.
The data below represents limited lot data.

Property	Condition	Method	Results	
Tensile Strength 0°	RTD	ASTM D 3039	305 ksi	2,103 MPa
Tensile Modulus 0°	RTD	ASTM D 3039	20.3 Msi	140 GPa
Tensile Strength 0°	ETW	ASTM D 3039	303 ksi	2,089 MPa
Tensile Modulus 0°	ETW	ASTM D 3039	19.5 Msi	134.4 GPa
Tensile Strength 0°	CTD	ASTM D 3039	293 ksi	2,018 MPa
Tensile Modulus 0°	CTD	ASTM D 3039	20 Msi	138 GPa
Poisson's Ratio	RTD		0.3	
Poisson's Ratio	ETW		0.29	
Poisson's Ratio	CTD		0.35	
Tensile Strength 90°	RTD	ASTM D3039	8.2 ksi	56.5 MPa
Tensile Modulus 90°	RTD	ASTM D3039	1.42 Msi	9.8 GPa
Tensile Strength 90°	ETW	ASTM D3039	4.9 ksi	33.8 MPa
Tensile Modulus 90°	ETW	ASTM D3039	1.18 Msi	8.1 GPa
Tensile Strength 90°	CTD	ASTM D3039	9.18 ksi	63.3 MPa
Tensile Modulus 90°	CTD	ASTM D3039	1.69 Msi	11.7 GPa
Compressive Strength 0°	RTD	ASTM D6641	251 ksi	1,730.6 MPa
Compressive Modulus 0°	RTD	ASTM D6641	19.27 Msi	133 GPa
Compressive Strength 0°	ETW	ASTM D6641	189 ksi	1,303 MPa
Compressive Modulus 0°	ETW	ASTM D6641	17.95 Msi	123.8 GPa
Compressive Strength 0°	CTD	ASTM D6641	291.7 ksi	2,011.2 MPa
Compressive Modulus 0°	CTD	ASTM D6641	19.4 Msi	133.7 GPa
Interlaminar Shear Strength	RTD	ASTM D2344	12 ksi	82.6 MPa
Interlaminar Shear Strength	ETW	ASTM D2344	8.62 ksi	59.4 MPa
Interlaminar Shear Strength	CTD	ASTM D2344	13 ksi	89.4 MPa
Open Hole Tensile Strength	RTD	ASTM D5766	58.8 ksi	405.4 MPa
Open Hole Tensile Strength	ETW	ASTM D5766	63.5 ksi	437.8 MPa
Open Hole Tensile Strength	CTD	ASTM D5766	56.1 ksi	386.8 MPa
Open Hole Comp. Strength	RTD	ASTM D6484	40.3 ksi	278 MPa
Open Hole Comp. Strength	ETW	ASTM D6484	37.6 ksi	259.2 MPa
Filled Hole Tensile Strength	RTD	ASTM D6742	68.3 ksi	470.9 MPa
Filled Hole Tensile Strength	ETW	ASTM D6742	69 ksi	475.7 MPa
Filled Hole Tensile Strength	CTD	ASTM D6742	63.4 ksi	437.1 MPa
In Plane Shear Str. (±45)	RTD	ASTM D3518	14.9 ksi	102.4 Msi
In Plane Shear Mod. (±45)	RTD	ASTM D3518	1.44 Msi	9.9 GPa
In Plane Shear Str. (±45)	ETW	ASTM D3518	13.42 ksi	92.5 MPa
In Plane Shear Mod. (±45)	ETW	ASTM D3518	0.92 Msi	6.3 GPa
Single Shear Bearing Str.	RTD	ASTM D5961	153.8 ksi	1,060.4 MPa
Single Shear Bearing Str.	ETW	ASTM D5961	106.3 ksi	732.9 MPa

Vacuum bag oven cure at 14.5 psi, normalized to 60% fiber volume, ETW: 180°F (82°C) Wet, CTD: -65°F (-54°C)
* Wet conditioning done at 145°F (63°C) and 85% RH until complete saturation

PRODUCT DATA SHEET

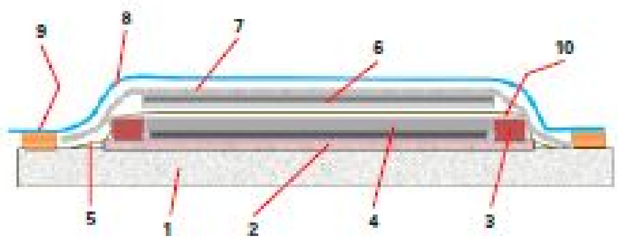
TENCATE

TC250 Resin System

COMPOSITE LAMINATE STACKING SEQUENCE

LIST OF MATERIALS

1. Tool – aluminum, steel, Invar, composite (tool plates must be release coated or film covered)
2. Release coat or film – Frekote 700NC or 770NC, FEP, TEDLAR
3. Silicone Edge Dams – Thicker than laminate
4. Laminate
5. Release coat or film – Frekote 700NC or 770NC, FEP, TEDLAR
6. Caul plate – aluminum, steel, Invar, silicone rubber sheet (metal caul plates must be release coated or wrapped)
7. 2.2 osy polyester breather – 1 or more
8. Vacuum bag
9. Vacuum sealant
10. Glass yarn string - (alternatively or additionally breather may wrap over top of dam to contact edge)



Revised 03/2016

All data given is based on representative samples of the materials in question. Since the method and circumstances under which these materials are processed and tested are key to their performance, and TenCate Advanced Composites has no assurance of how its customers will use the material, the corporation cannot guarantee these properties.

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Titanium 40 mm Tube Clamp Adapter

For 40 mm (heavy duty) tubing, with standard adult female, for standard adult componetry. Two side clamping screws for added safety. For 40 mm tube clamp rated for 500 pounds for heavy duty componetry, see HDT-TCA-1S.

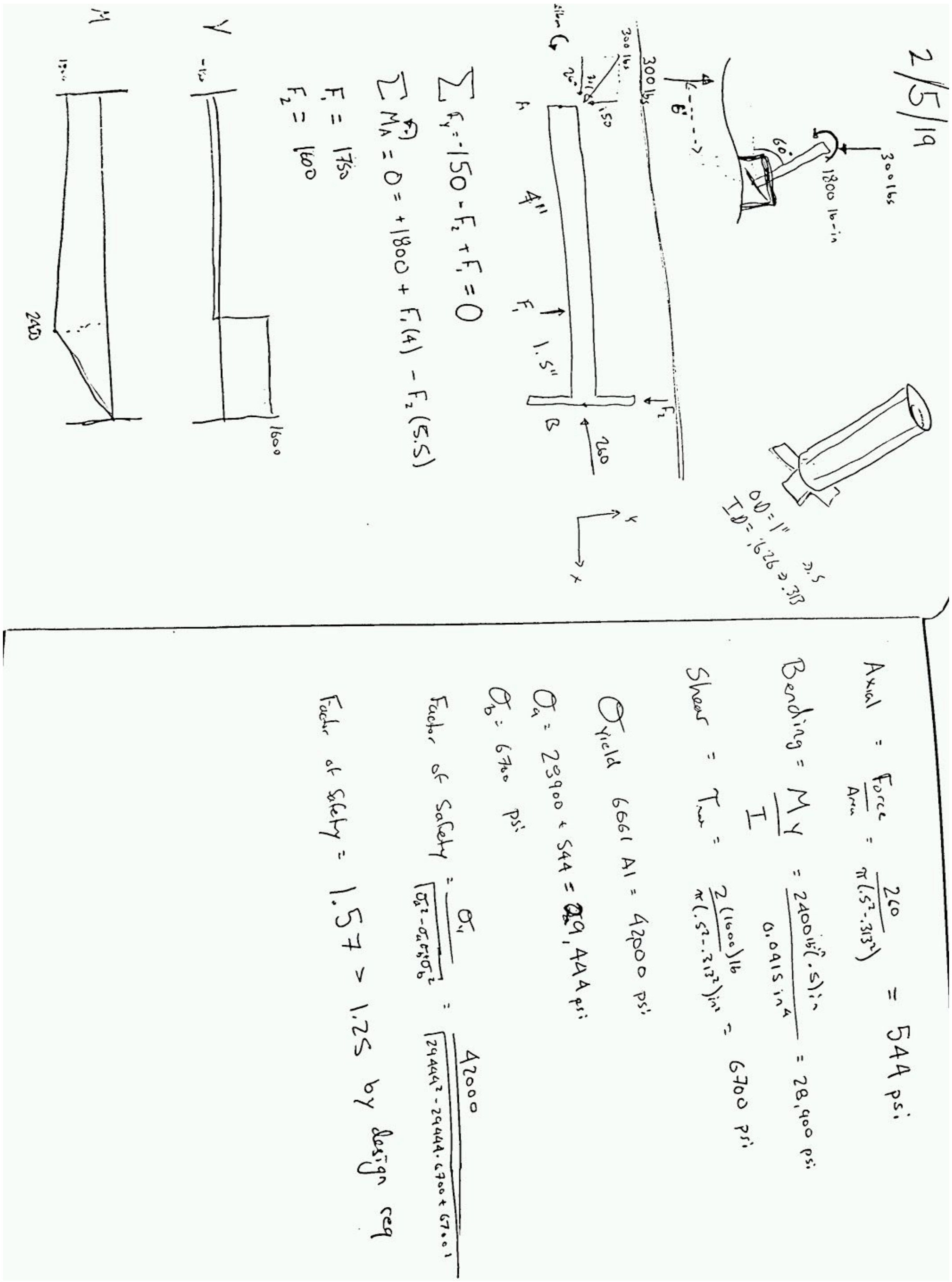
- **Material:** Titanium
- **Weight Limit:** 375 lb 170.1 kg
- **Part Weight:** 5.185 oz 146.9 kg
- **Part Height:** 53.50 mm
- **Receiver Screws:** (4) M8x16 socket set screws - Torque 13-14 Nm
- **Clamping Screw:** (2) M6x20SHCS, with washers - Torque 6-7 Nm, alternate

4-Hole Male - Tough Dog Series

- **Material:** Titanium
- **Weight Limit:** 365 lb 165 kg
- **Part Weight:** 2.485 oz 70 g
- **Part Height:** 22.27 mm
- **4-Hole Size:** M6
- **4-Hole Pattern:** 65 mm

Appendix E: Detailed supporting analysis

Post Strength Analysis



Upper Post Height Analysis

Height range of Military = 58 in to 80 in
Hmax = 80 Hmin = 58
Anthropormetric value for bottom of foot to knee = 0.285 HM
Approximate Height of prosthetic foot = Hp = 3 in
Length of below knee residual limb to maintain knee use = Hr = 15 cm or 5.9 in
Pyramid connectors = Hpc = 2 in
Post Height = PH = 0.285H - Hp - Hr - Hpc
PHmax = 0.285 (80) - 3 - 5.9 - 2
PHmax = 11.9”

Lower post length = lp = 3in
Post = 11.9 - 3 = 8.9”
Overlap = 0.5”
Maximum post length = 9.5”
Verification = 9.5’ + 3” - .5” = 12”
Minimum post length = 3.5”
Mid post length = 6.5”

Composite Foot Analysis

Surf Leg Composite
MATLAB CODE:

Laminate 1
Symmetric Balanced Layup Configuration

```
theta=[0 0 0 90 0 0 0 45 -45 45 -45 0 0 0 0 -45 45 -45 45 0 0 0 90 0 0 0];
% angles of each ply, total number of layers is 26
number_of_plies=length(theta)
tply=0.00625; % ply thickness in inches
t=tply*length(theta) % total thickness of laminate
```

```
Area=12*3 % surface area

% Material Properties
% Carbon/Epoxy Uni-tape pre-preg material
% Material Properties fr TC250 Resin System
% Material is found in the composites lab at Cal Poly

T_amb=75; %degree F
T_cure=265; % degree F
Tg=285; % degree F
F1t=305e3; % psi
E1=20.3e6; % psi
v12=0.3;
F2t=8.2e3; % psi
E2=1.42e6; % psi
v21=(v12*E2)/E1;
Fc=250e3; % psi
F6=14.9e3; % psi
G12=1.44e6; % psi


Q11=E1/(1-v12*v21);
Q12=(v12*E2)/(1-v12*v21);
Q21=Q12;
Q22=E2/(1-v12*v21);
Q66=G12;

Q=[Q11 Q12 0   % Calculating Q
    Q21 Q22 0
    0 0 Q66];

for i=1:length(theta)
m=cos(theta);
n=sin(theta);
Tsig{i}=[m(i)^2 n(i)^2 2*m(i)*n(i)
    n(i)^2 m(i)^2 -2*m(i)*n(i)
    -m(i)*n(i) m(i)*n(i) m(i)^2-n(i)^2];

Tep{i}=[m(i)^2 n(i)^2 m(i)*n(i)
    n(i)^2 m(i)^2 -m(i)*n(i)
    -2*m(i)*n(i) 2*m(i)*n(i) m(i)^2-n(i)^2];

Qbar{i}=Tsig{i}^-1*Q*Tep{i}; % Transformation of Q to Qbar
end
```

```
zk = [];
zk(1) = tply;
for r=2:length(theta)
    zk(r)=zk(r-1)+t;
    zk_1(r)=zk(r-1);
    zkbar(r)=(zk(r)^2-zk_1(r)^2)/2;
    z3(r)=(zk(r)^3-zk_1(r)^3)/3;
end

A=zeros(3,3);
B=zeros(3,3);
D=zeros(3,3);
for n=1:length(theta)
    A=A+Qbar{n}*tply;
    B=B+(Qbar{n}*zkbar(n));
    D=D+(Qbar{n}*z3(n));
 end
A_1=sum(A,26)
B_1=sum(B,26)
D_1=sum(D,26)


clearvars -except A_1 B_1 D_1
number_of_plies = 26


t =
    0.1625
Area =
    36
A_1 =
   1.0e+06 *
    2.2592    0.2525   -0.0247
    0.2525    0.9270   -0.0704
   -0.0247   -0.0704    0.4168
B_1 =
   1.0e+08 *
    1.1516    0.1285   -0.0126
    0.1285    0.4717   -0.0358
   -0.0126   -0.0358    0.2122
D_1 =
   1.0e+08 *
    3.2949    0.3152   -0.0362
```

```
    0.3152    1.1747   -0.1058
   -0.0362   -0.1058    0.5423
```

Laminate 2

Layup configuration with less zeros total. This gives a total percentage of 0 plies of 36% of total plies which will make the laminate less stiff.

```
theta=[0 90 0 45 -45 45 -45 0 0 -45 45 -45 45 0 90 0];
% angles of each ply, total number of layers is 16
number_of_plies=length(theta)
tply=0.00625; % ply thickness in inches
t=tply*length(theta) % total thickness of laminate

% Material Properties
F1t=305e3; % psi
E1=20.3e6; % psi
v12=0.3;
F2t=8.2e3; % psi
E2=1.42e6; % psi
v21=(v12*E2)/E1;
Fc=250e3; % psi
F6=14.9e3; % psi
G12=1.44e6; % psi

Q11=E1/(1-v12*v21);
Q12=(v12*E2)/(1-v12*v21);
Q21=Q12;
Q22=E2/(1-v12*v21);
Q66=G12;

Q=[Q11 Q12 0   % Calculating Q
    Q21 Q22 0
    0 0 Q66];

for i=1:length(theta)
m=cos(theta);
n=sin(theta);
Tsig{i}=[m(i)^2 n(i)^2 2*m(i)*n(i)
    n(i)^2 m(i)^2 -2*m(i)*n(i)
    -m(i)*n(i) m(i)*n(i) m(i)^2-n(i)^2];

Tep{i}=[m(i)^2 n(i)^2 m(i)*n(i)
    n(i)^2 m(i)^2 -m(i)*n(i)
    -2*m(i)*n(i) 2*m(i)*n(i) m(i)^2-n(i)^2];

Qbar{i}=Tsig{i}^-1*Q*Tep{i}; % Transformation of Q to Qbar
end
```

```
zk = [];
zk(1) = tply;
for r=2:length(theta)
    zk(r)=zk(r-1)+t;
    zk_1(r)=zk(r-1);
    zkbar(r)=(zk(r)^2-zk_1(r)^2)/2;
    z3(r)=(zk(r)^3-zk_1(r)^3)/3;
end

A=zeros(3,3);
B=zeros(3,3);
D=zeros(3,3);
for n=1:length(theta)
    A=A+Qbar{n}*tply;
    B=B+(Qbar{n}*zkbar(n));
    D=D+(Qbar{n}*z3(n));
 end
A_2=sum(A,26)
B_2=sum(B,26)
D_2=sum(D,26)

clearvars -except A_2 B_2 D_2
```

```
number_of_plies =
    16
t =
    0.1000
A_2 =
   1.0e+05 *
    9.8240    2.2569   -0.2473
    2.2569    8.3771   -0.7040
   -0.2473   -0.7040    3.2682
B_2 =
   1.0e+07 *
    1.1191    0.2552   -0.0279
    0.2552    0.9472   -0.0796
   -0.0279   -0.0796    0.3699

D_2 =
1.0e+07 *
    1.1926    0.2406   -0.0300
    0.2406    0.9137   -0.0900
```

```
   -0.0300   -0.0900    0.3558
```

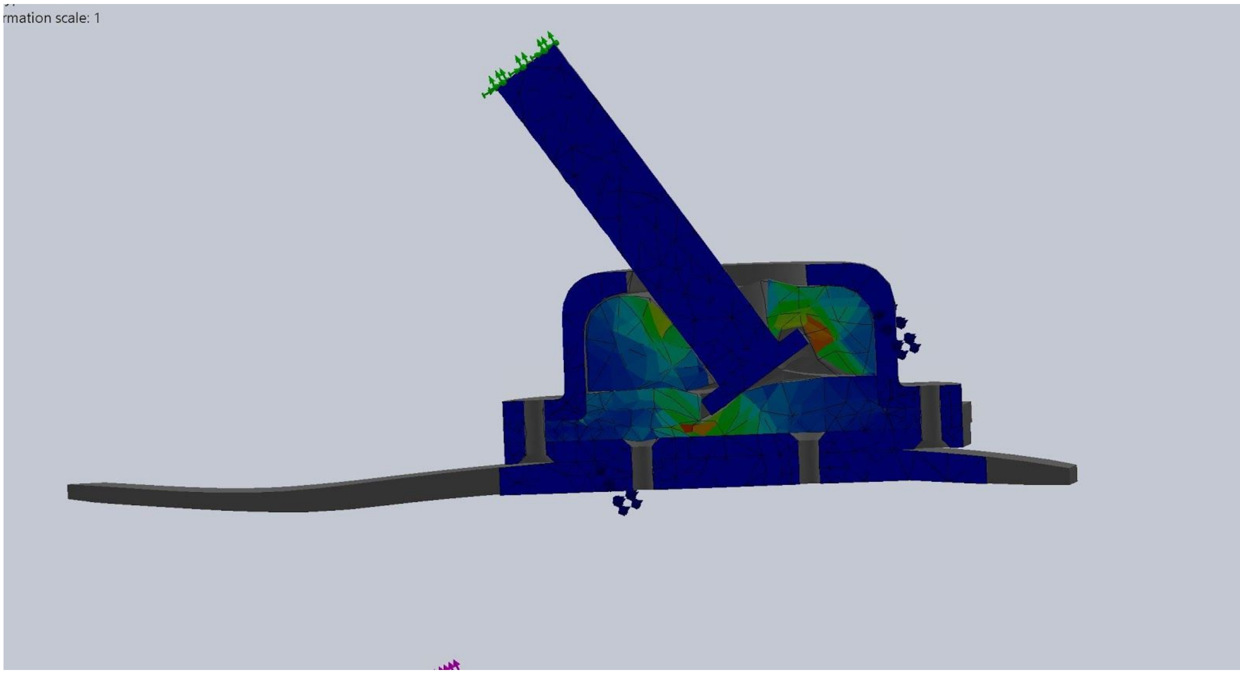
Laminate 3

```
theta=[0 0 45 -45 45 -45 0 0 0 0 -45 45 -45 45 0 0];
% angles of each ply, total number of layers is 14
number_of_plies=length(theta)
tply=0.00625; % ply thickness in inches
t=tply*length(theta) % total thickness of laminate

% Material Properties
F1t=305e3; % psi
E1=20.3e6; % psi
v12=0.3;
F2t=8.2e3; % psi
E2=1.42e6; % psi
v21=(v12*E2)/E1;
Fc=250e3; % psi
F6=14.9e3; % psi
G12=1.44e6; % psi

Q11=E1/(1-v12*v21);
Q12=(v12*E2)/(1-v12*v21);
Q21=Q12;
Q22=E2/(1-v12*v21);
Q66=G12;

Q=[Q11 Q12 0   % Calculating Q, reduced stiffness matrix
    Q21 Q22 0
    0 0 Q66];

for i=1:length(theta)
m=cos(theta);
n=sin(theta);
Tsig{i}=[m(i)^2 n(i)^2 2*m(i)*n(i)
    n(i)^2 m(i)^2 -2*m(i)*n(i)
    -m(i)*n(i) m(i)*n(i) m(i)^2-n(i)^2];

Tep{i}=[m(i)^2 n(i)^2 m(i)*n(i)
    n(i)^2 m(i)^2 -m(i)*n(i)
    -2*m(i)*n(i) 2*m(i)*n(i) m(i)^2-n(i)^2];

Qbar{i}=Tsig{i}^-1*Q*Tep{i}; % Transformation of Q to Qbar
end
```

```
zk = [];
zk(1) = tply;
for r=2:length(theta)
    zk(r)=zk(r-1)+t;
    zk_1(r)=zk(r-1);
    zkbar(r)=(zk(r)^2-zk_1(r)^2)/2;
    z3(r)=(zk(r)^3-zk_1(r)^3)/3;
end

A=zeros(3,3);
B=zeros(3,3);
D=zeros(3,3);
for n=1:length(theta)
    A=A+Qbar{n}*tply;
    B=B+(Qbar{n}*zkbar(n));
    D=D+(Qbar{n}*z3(n));
 end
A_toes=sum(A,26)
B_toes=sum(B,26)
D_toes=sum(D,26)
```

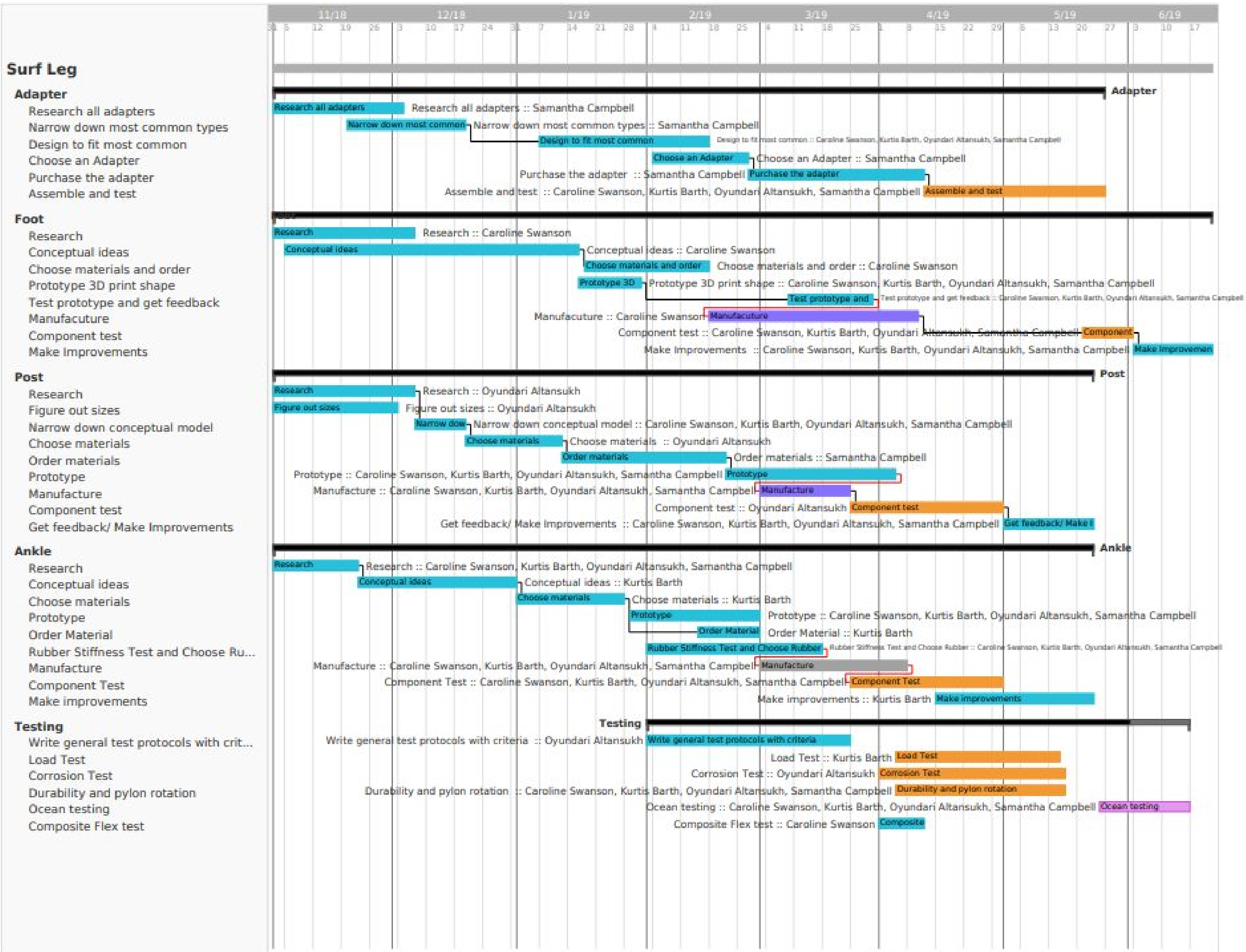
```
number_of_plies =
    16
t =    0.1000
A_toes =
   1.0e+06 *
    1.2028    0.1951         0
    0.1951    0.6785         0
         0         0    0.2963
B_toes =
   1.0e+07 *
    1.3681    0.2207    0.0000
    0.2207    0.7673    0.0000
    0.0000    0.0000    0.3354
D_toes =
   1.0e+07 *
    1.4237    0.2126    0.0087
    0.2126    0.7387    0.0185
    0.0087    0.0185    0.3278
```

Published with MATLAB® R2018a



During the design we performed FEA analysis. Here the bushing are shown with 1000 psi and a 150 lbf load. We used the values and the deformed model to determine the cross size for the post and the rubber rating to use.

Appendix F: Gantt Chart



Appendix G: Safety Checklist

SENIOR PROJECT CRITICAL DESIGN REVIEW HAZARD IDENTIFICATION CHECKLIST

Y	N	
☐	☐	Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
☐	☐	Can any part of the design undergo high accelerations/decelerations?
☐	☐	Will the system have any large moving masses or large forces?
☐	☐	Will the system produce a projectile?
☐	☐	Would it be possible for the system to fall under gravity creating injury?
☐	☐	Will a user be exposed to overhanging weights as part of the design?
☐	☐	Will the system have any sharp edges?
☐	☐	Will all the electrical systems properly grounded?
☐	☐	Will there be any large batteries or electrical voltage in the system above 40 V either AC or DC?
☐	☐	Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
☐	☐	Will there be any explosive or flammable liquids, gases, dust fuel part of the system?
☐	☐	Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
☐	☐	Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
☐	☐	Can the system generate high levels of noise?
☐	☐	Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures ,etc…?
☐	☐	Will the system easier to use safely than unsafely?
☐	☐	Will there be any other potential hazards not listed above? If yes, please explain below?

Appendix H: User guide for the prosthetic Leg

Included with the prosthetic leg is multiple different rubber parts to customize the movement to the user. In order to change out the rubber both the water shoe and upper post must be removed from the foot. This will expose the 6 bolts and nuts that hold the upper cap in place, the nuts must be unscrewed. The removal of the nuts will allow for the separation of the shell and bottom of the foot.
After the cap has been separated the upper and lower rubber pieces may be removed and replaced with the proper rubber. The choice of the rubber type is dependent on how the user feels while using the prosthetic foot, our recommendations for the rubber is:
85 - for users 210 lbs and up
70 - for users 165 lbs - 210 lbs
44- for users in the weight of 120 lbs -165lbs
35- for users below 120 lbs

The upper rubber controls the ability of forward and back movement (dorsiflexion and plantar flexion), as well as side to side movement (inversion and eversion) of the foot. While, the lower rubber controls for the ability of the foot to have a slight twist (pronation and supination) movement. Once the rubbers have been chosen, the foot must be put back together.

To put the rubber back onto the foot, the user should take into account the cross at the bottom of the lower post, each piece of rubber also has a cross indentation. The user should take special notice of the smallest segment of the post, this piece of the cross should always be pointing to the front of the foot. Using the cross as an indicator of the front, make sure to test the lower rubber before placing on the bolts

The other aspect of this adjustable foot is to select the post for the correct height of the prosthetic. The recommendation for this is to sit the users walking prosthetic foot next to the surfing prosthetic foot, then using the bike seat clamp, slide and tighten the prosthetic to the desired height.

-If the height of the prosthetic requires another post length, both post clamp adaptor and the bicycle clamp can be removed and transferred to another post. Making sure to tighten both tightly on to the new post.

To connect the prosthetic to the users socket, first the socket connection must be determined:

-If the socket has a four hole connection to attach the prosthetic to the socket please use the four hole pyramid adaptor that is included along with the prosthetic foot.

-If the socket has a pyramid connection, then the post clamp adaptor can be used alone.

When connecting the post clamp pyramid adaptor to the socket the recommended way is to go around the post clamp adaptor and screw each screw in slightly, and then go around the circle repeating until the post is fully connected to the socket. This is done to ensure that the leg is connected straight on the post, and not at an angle.

After the leg has been adjusted and connected to the leg, the user should test out the movements on land. This will ensure that the rubber stiffness is the best fit, the height is proper and the connection on the leg is secure.

The surf booty should then be attached over the foot and the user may proceed into the water. Have fun surfing and Hang Five!